ENHANCING REHABILITATION FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

Submitted by Andrea Kay Bailey to the University of Exeter as thesis of the degree of Doctor of Philosophy in Sports and Health Sciences

In January 2015

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Conclusion: Is there evidence that NCON rehabilitation improves self-perceived (subjective) outcomes of function, and objectively-measured functional, musculoskeletal and neuromuscular performance following ACL reconstruction compared to traditional CON practice?

Are there significant relationships amongst the subjective (self-perceived) measure of knee function (IKDC) and objective measures of function (HOP), musculoskeletal (ATFD, PF) neuromuscular performance (RFD, EMD, SMP) at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery?

Conclusion: Are there significant relationships amongst subjective (self-perceived) measure of knee function (IKDC) and objective measures of function (HOP), musculoskeletal (ATFD, PF) neuromuscular performance (RFD, EMD, SMP) at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery?

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Publications


**Poster Presentations**

Bailey AK, Gleeson NP, Rees D, Roberts SNJ, Eston R, Richardson J.

Non-concurrent strength and endurance rehabilitation improves short-term functional, neuromuscular and sensorimotor outcomes following both autologous chondrocyte implantation (ACI) repair of chondral lesions and anterior cruciate ligament (ACL) reconstruction. *Oswestry Research Day 2010*.

Bailey AK, Gleeson NP, Rees D, Roberts SNJ, Eston R, Richardson J.

Non-Concurrent Rehabilitation Improves Short Term Neuromuscular Outcomes Following Autologous Chondrocyte Implantation (ACI). *Oswestry Research Day 2009*. 

Bailey, A.K; Gleeson, N.P; Rees, D; Roberts, S.N.J; Eston, R; Richardson, J. The effects of non-concurrent strength and endurance rehabilitation on neuromuscular and musculoskeletal performance following anterior cruciate ligament or autologous chondrocyte implantation reconstruction surgery to knees. Random control trials. *Oswestry Research Day 2008.*

**Podium Presentation**


Bailey AK, Gleeson NP, Rees D, Roberts SNJ, Eston R, Richardson J.

The Rehabilitation of the Oswestry Autologous
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This Thesis is dedicated to Dai Rees.
**Thesis Title: Enhancing rehabilitation following anterior cruciate ligament reconstruction.**

**Context:** Physical training with a neuromuscular focus has been shown to reduce anterior cruciate ligament (ACL) injury. However, ACL injury remains prevalent and often leads to joint instability, which requires surgical reconstruction. Following reconstructive surgery, a minimum of 6 months supervised rehabilitation is recommended with associated with financial cost implications to the National Health Service (NHS), the patient and society. Traditionally rehabilitation is offered in a concurrent format, whereby strength and cardio-vascular endurance exercises are performed in the same session. However, accumulating evidence from healthy populations, suggests that the development of strength might be attenuated by cardio-vascular endurance conditioning performed in close temporal proximity. This thesis comprises an entirely novel investigation of potential attenuation of strength gains in rehabilitating clinical populations that is associated with temporal incompatibility of physiological conditioning stimuli. No study has previously investigated this phenomenon, whether it might compromise the efficacy of treatment or recovery, or its potential influence on objectively-measured and patients’ perception of functional, musculoskeletal and neuromuscular performance capabilities. **Objectives:** The purpose of this thesis was to assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on (a) subjective (IKDC; KOOS; PP [Chapter 4]) and objective measures of function (HOP [Chapter 5]) (primary outcome measures for this thesis), and (b) objective measures of musculoskeletal (ATFD) and neuromuscular performance (PF, EMD, RFD, SMP [Chapter 5]) (secondary outcome measures), in patients with anterior cruciate
ligament deficiency. The secondary aim was to evaluate the relationships amongst a subjective outcome of function (IKDC), an objective outcome of function (HOP), and the secondary objective outcomes of musculoskeletal (ATFD) and neuromuscular (PF, RFD, EMD, SMP) performance at pre-surgery and at 24 weeks post-surgery (Chapter 6). **Setting:** Orthopaedic Hospital NHS Foundation Trust. **Design:** Prospective random-allocation to group trial involving iso-volume rehabilitative intervention versus contemporary practice, using contralateral limb assessment and clinico-social approbation controls. The design compared the effects of experimental post-surgical rehabilitation comprising non-concurrent strength and endurance conditioning with two conditions of control reflecting contemporary clinical practice (matched versus minimal assessment interaction). **Participants:** Eighty two patients (69♂, 13♀, age: 35.4 ± 8.6 yr; time from injury to surgery 9.4 ± 6.9 months [mean ± SD]) electing to undergo unilateral ACL reconstructive surgery (semitendinosus and gracilis graft [n = 57]; central third, bone-patella tendon-bone graft [n = 25]); were allocated to groups (2:2:1 purposive sampling ratio, respectively). Nineteen patients were lost to follow-up. **Intervention:** A standardised traditional concurrent (CON) ACL rehabilitation programme acted as the control versus an experimental non-concurrent (NCON) ACL rehabilitation programme that involved separation of strength and cardio-vascular endurance conditioning. An additional control group (Limited testing CON) matched the CON group rehabilitation applied within contemporary clinical practice. **Outcome Measures:** Chapter 4: The self-perceived primary outcome measures of function IKDC, KOOS and PP were assessed on five separate occasions (pre-surgery, and at 6, 12, 24 and 48 weeks post-surgery). However, assessment occasions were purposefully reduced to pre-operative and 48
weeks post-operative for the Limited testing CON group. Chapter 5: The primary objective outcome of function was HOP; the secondary outcomes were ATFD, PF, RFD, EMD and SMP associated with the knee extensors and flexors of the injured and non-injured legs. These objective outcomes were assessed on five separate occasions (pre-surgery, and at 6, 12, 24 and 48 weeks post-surgery). However, assessment occasions were purposefully reduced to pre-operative and at 48 weeks post-operative only for the Limited testing CON group. Chapter 6 Self-perceived (IKDC) subjective knee evaluation and the objective outcome of function (HOP), and selected objective outcomes of musculoskeletal and neuromuscular performance including ATFD, PF, RFD, EMD and SMP of the knee extensors and flexors of the injured and non-injured legs where applicable; measured at pre-surgery and at 24 weeks post-surgery were analysed for association, using Pearson product-moment correlation coefficients. A priori alpha levels were set at \( p < 0.05 \). Results: Chapter 4: Factorial analyses of variance (ANOVAs) with repeated-measures investigating the primary aim showed significant group (NCON; CON) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) interactions for self-perceived outcomes of function IKDC, KOOS and PP confirmed increased clinical effectiveness of NCON conditioning \( F_{(2.0, 82.9)} GG = 4.0 p < 0.05, F_{(2.2, 134.7)} GG = 5.5 p < 0.001, F_{(1.9, 121.4)} GG = 14.6 p < 0.001 \), respectively and the group mean peak relative difference in improvement for NCON was \(~5.9\% - 12.7\%\) superior to CON. The greatest interaction effect was found to occur between pre-surgery and the 12 weeks post-operative test occasion for IKDC and KOOS, and between pre-surgery and the 24 week test occasion for PP. Patterns of improvements in self-perceived fitness over time were represented by a relative effect size range of 0.71 to 1.92. Improvement patterns were not significantly
different between control groups offering matched or minimised assessor-patient interaction (CON vs. Limited testing CON; pre-surgery vs. 48 weeks post-surgery) indicating that clinical approbation by patients had not contributed to the outcome.  *Chapter 5:* Factorial analyses of variance (ANOVAs) with repeated-measures showed significant group (NCON; CON) by leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) interactions of the objective measure of function (HOP) together with the secondary outcomes of ATFD, PF, RFD, EMD and SMP. Similar responses were noted for the knee extensors and flexors of the injured and non-injured legs \(F_{(2.1, 248)} GG = 4.5 \text{ to } 6.6; p<0.01\) and confirmed increased clinical effectiveness of NCON conditioning (range \(\sim 4.7% - 15.3\% \text{ [10.8%]}\)) better than CON between 12 and 48 weeks. Patterns of improvements in physical fitness capabilities over time were represented by a relative effect size range of 1.92 to 2.89. Improvement patterns were not significantly different between control groups offering matched or minimised assessor-patient interaction (CON vs. Limited testing CON; pre-surgery versus 48 weeks post-surgery) indicating that clinical approbation by patients had not contributed to the outcome.  *Chapter 6:* Two-tailed probabilities were used due to the exploratory nature of this study. A limited number of weak to moderate statistically significant correlations were confirmed (ranging from \(r = 0.262 - 0.404; p<0.05; n=48 \text{ [amalgamated NCON and CON groups] }\) between IKDC and most notably, the neuromuscular performance outcome of EMD.  **Conclusion:** Overall, the patterning and extent of changes amongst self-perceived, functional, musculoskeletal and neuromuscular performance scores offer support for the efficacy of using non-concurrent strength and endurance conditioning to enhance post-surgery rehabilitation. The limited robustness of
relationships amongst the validated and frequently-used self-perceived outcome of function [IKDC], and objectively-measured outcomes of function and musculoskeletal and neuromuscular performance suggested that each might properly reflect an important but separate aspect of clinical response and should be deployed to detect change.
Chapter 1:

General Introduction
Chapter 1: General Introduction

This thesis investigates a new phasing of exercise following anterior cruciate ligament (ACL) surgery. The following chapter introduces the key topics associated with the context of the study. In particular, it offers a brief background as to why both the post-operative ACL populations and the selection of outcome measures were chosen, and as to why the experimental intervention was of great clinical interest. Finally the aims of the thesis are presented.

1.1 Anterior cruciate ligament

1.1.1 Anatomy

A literature review by Zantop et al. (2005) provides a basic overview of the anatomy of the anterior cruciate ligament (ACL). The ACL is an intra-articular ligament made up of two bundles of dense connective tissue the anteromedial (AM) and posterolateral (PL) bundle and collectively they are enveloped into the synovial membrane of the knee. The ACL originates from the medial side of the lateral femoral condyle and runs obliquely through the intercondylar notch and inserts into the medial tibial eminence. The width of the ACL has been reported to be between 7mm – 12mm, it is at its narrowest mid-substance, fanning out towards its insertion. When the knee is extended the PL bundle is tight and the AM bundle is relatively lax. In flexion the femoral attachment of the ACL becomes more horizontal and the AM bundle is tight and the PL bundle more relaxed. The ACL has a blood supply from the middle genicular artery proximally and by the lateral and inferior genicular artery distally. Most of the ACL nerve receptors are Ruffini receptors functioning as
stretch receptors and nociceptors. These receptors are located in the subsynovial layer of the ACL and near its insertions. The mechanical functions of the ACL are to check anterior translation of the tibia on the femur and to restrain internal rotation of the femur on the tibia. Therefore, injury to the ACL can lead to functional instability. The following section introduces the propensity of ACL injury.

Figure 1.1  Illustration of the anterior aspect of the right knee (patella removed for visualisation of the intra-articular ligaments). Sandring 2009 (Grey’s Anatomy [40th Ed.]).
1.1.2 Injury

The knee is one of the most commonly injured joints of the human body and carries an increased risk of injury with sports participation. Recent research states approximately 40% of all ligamentous knee injuries are ACL related and 70% of all ACL injuries occur during sports (Lam et al. 2009). Sporting activities involving jumping, cutting and decelerating are ranked the highest provokers of ACL injury (Renstrom 2008), therefore injuries to the ACL are commonplace in many sports including football, basketball, skiing, netball, volleyball and rugby (Alentorn-Geli et al. 2009, Lam et al. 2009). Injury to the ACL can lead to recurrent episodes of instability at the knee joint, increasing the risk of further injury. However, with the advancement of surgery and rehabilitation, rupture of the ACL is no longer thought to be a career threatening injury. Bjordal (1997) estimates 89% of professional football players’ return to their previous level of sport. Yet, more recent findings suggest up to two thirds of patients have not returned to full function one year after surgery (Ardern et al. 2011a). Patients traditionally require a minimum of six months of formal rehabilitation (van Grinsven et al. 2010, Lobb et al. 2012, Manske et al. 2012) and this can contribute to both the cost to the NHS and to time off work/sport for the patient. Ultimately, this injury does have substantial financial, emotional and physical implications.

1.1.3 Post-operative rehabilitation

Many studies have been performed over the years with respect to evaluating ACL surgery, outcomes and rehabilitation (e.g. Risberg et al. 2001, Risberg et al. 2004, Freedman et al. 2003, Beynnon et al. 2005, Griffin et al. 2006, Trees et al. 2009, van Grinsven et al. 2009). Recently, the focus of much
of the research is perturbation training and injury prevention (e.g. Myer et al. 2004, Noyes et al. 2005, Hewitt et al. 2006, Renstrom et al. 2008). Perturbation training (which can involve sport-specific and dynamic proprioceptive exercises) is common in ACL rehabilitation following surgery in an attempt to lessen the likelihood of recurrence and possibly, to correct the cause for the initial injury (van Grinsven et al. 2009, Trees et al. 2009). A Cochrane Collaboration review by Trees et al. (2009) focused on ACL rehabilitation and it highlighted great variations in methodological study scores, nature of participant, assessor blinding, outcome measures and time points reported, therefore pooling of most of the data was not valid and could not provide sufficient evidence to support one exercise intervention for ACL rehabilitation against another. The summation and recommendation of this report was that further randomised controlled studies with appropriate outcome measures and surveillance periods using standardised reporting, were required. Therefore, it is apparent that a gap in the literature remains for a robust randomised control trial focusing on rehabilitation and using validated outcome measures over a significant time scale.

1.2 Concurrent versus non-concurrent conditioning

strength, endurance and a combination of strength and endurance. The findings showed no difference in VO$_{2\text{max}}$ for the cardio-vascular endurance and concurrent group. However, there were reduced strength gains at the 9 - 10 week stage in the concurrent group compared to that of the pure strength group. Hickson concluded that there is little or no benefit for endurance athletes to strength train at the same time, and it could be deleterious for strength athletes to perform high endurance activities while simultaneously training for strength. However, it could be argued that this 10-week study did not allow enough time to show lasting physiological responses, nor did it allow for periodisation. However, further research substantiates that high intensity endurance training compromises strength (Dudley and Djamil 1985, Hunter et al 1987, Sale et al. 1990, Nelson et al. 1990, Hennessy and Watson 1994, Kraemer et al. 1995, Bell et al. 2000, Häkkinen et al. 2003, Santtila et al. 2009, Häkkinen et al 2003). Conversely, other studies (Bell et al. 1991, Volpe et al 1993, McCarthy et al. 1995, Gravelle at al 2000, McCarthy et al. 2002, Balabinis et al. 2003, Leveritt et al. 2003, Kraemer 2004 Glowacki et al.2004, Karavirta et al. 2011) have shown no strength attenuation.

To date no studies have investigated whether or not contemporary rehabilitation practices involving concurrent conditioning for strength and endurance performance adversely attenuate the extent or rate of improvement in indices in self-perceived, objectively-measured indices of function, musculoskeletal and neuromuscular performance. It is important to note that the outcome of such a study could not only influence the rehabilitation following well established surgeries, for example ACL reconstruction post-surgical/ injury rehabilitation, but also have a wider reaching effect across all areas of
rehabilitation that involve a substantive period of musculoskeletal and neuromuscular training.

1.3 Implications for clinical outcomes

Subjective outcome, self-perceived performance, patient-reported measure, etc. are interchangeable terms that are traditionally used to evaluate how the patient rates his or her function following injury or surgery. Some of the most commonly used in knee surgery are International Knee Documentation Committee subjective knee evaluation form (IKDC), Lysholm knee scoring scale, Short Form 12 (SF12), Knee injury and Osteoarthritis Outcome Score (KOOS), the Knee Injury and Osteoarthritis Outcome Score Physical Function Short Form (KOOS-PS), the Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL), the Oxford Knee Score (KOS), the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the Activity Rating Scale (ARS) and the Tegner Activity Score (TAS) (Roos et al. 1998, Irrgang et al. 2001, Lohmander et al. 2004, Hambly 2010, Collins et al. 2011, Irrgang et al. 2012). A self-perceived outcome is always desirable as patient’s satisfaction is always the main goal of surgery and rehabilitation, but surprisingly, there is very little evidence focusing on this patient centred and individualised outcome (Kvist 2004, Heijne 2008). This may be because patient’s satisfaction is very complex and contains multiple dimensions. Yet, despite the psychological impact surgery and rehabilitation have, it is evident that there is a gap in personalised performance systems following surgery and our understanding of the impact this has on returning to full function. However, the potential utility of the performance profile technique in measuring and addressing the patient’s perceived factors in conjunction with physical rehabilitation may provide some
answers (Doyle et al. 1998, Gleeson et al. 2008). However, when used in isolation, self-perceived outcome measures do have limitations and some have shown to have limited correlation with functional outcomes or in predicting a return to full function (Fitzgerald et al. 2000, Fitzgerald et al. 2001, Reid et al. 2007, Möller et al. 2009, Ardern 2010). Therefore, the inclusion of objective measures when analysing recovery from surgery is advisable.

Objective measures of function such as hop for distance, vertical jump, shuttle-runs, etc. are commonly used performance tests (Fitzgerald et al. 2000, Fitzgerald et al. 2001, Clark 2001, Gustvasson et al. 2006, Thomeé et al. 2011). This type of test allows the clinician to holistically assess stability, strength, rate of force development, power, proprioception, neuromuscular control, dynamic balance and confidence (Clarke 2001). These are all key factors that rehabilitation aims to improve. Indeed some of these physical components (strength, rate of force development, for example) that are required to demonstrate a hop can be measured in isolation. They are also considered to be integral elements in knee joint stability.

One conceptual model of stabilisation of synovial joint systems suggests avoidance of musculoskeletal injury might be associated with resistance to fatigue and superior neuromuscular performance (Gleeson et al. 1998). Thus, any strategy for rehabilitative conditioning that might tend to heighten the development of either musculoskeletal and/or neuromuscular performance may in turn hinder the potential for injury of a synovial joint. This may be either prior to musculoskeletal trauma or reconstruction surgery and where applicable, subsequent rehabilitation and resumption of functional activities. In the case of the latter clinical scenario, an optimum interaction between the efforts of the surgical intervention and the mode of physical rehabilitation conditioning will
determine the successful clinical outcome. Furthermore, no studies to date have investigated whether or not attenuation of strength performance associated with concurrent conditioning for endurance performance also affects other potential important indices of neuromuscular performance for stabilization of synovial joints such as rate of force development and electromechanical delay.

Optimised musculoskeletal and neuromuscular performance is important to the capability for dynamic stabilisation for joint health and protection from injury (Gleeson et al. 1996a and 1996b, Gleeson et al. 1998, Gleeson et al. 2000, Myer et al. 2004, Hewitt et al. 2006, Minshull et al. 2007). Thus, any clinical intervention that might involve the potential for physiological incompatibility of concurrent strength and endurance conditioning and whose influence might intrude substantively on an expected dose-response outcome during exercise conditioning, would be worthy of investigation in order to properly inform evidence-based, clinical practice.

Although prospective neuromuscular interventions aimed at injury prevention do reduce ACL injury, it is not yet known what or which components are involved (Hewitt et al. 2006). Therefore, it is prudent to use a battery of musculoskeletal and neuromuscular tests.
1.4 Study Aims

General Aim

The general purpose of this thesis is to investigate the effects of reconstruction surgery and non-concurrent strength and endurance rehabilitation on the self-perceived, musculoskeletal, and neuromuscular performance on a traumatised knee joint.

The focus of attention will be on the knee, as it is one of the most frequently injured synovial joints during sporting and occupational endeavours. The study will address ACL reconstructive surgery as the ACL is one of the most common of the knee ligamentous injuries. The rehabilitation following ACL reconstructive surgery utilises a proven rehabilitation protocol in current clinical practice at the NHS Foundation Trust Orthopaedic Hospital that involves extensive use of concurrent strength and endurance conditioning [Appendix A - RJAH anterior cruciate ligament rehabilitation guide].

Specific Aims

Specific aims will include:

- To assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on self-perceived (subjective) measures of function (IKDC, KOOS, PP), in patients with anterior cruciate ligament deficiency (Chapter 4).
- To assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on HOP as an objective measure of function, in patients with anterior cruciate ligament deficiency (Chapter 5).
• To assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on objective measures of musculoskeletal (ATFD) and neuromuscular performance (PF, EMD, RFD, SMP), in patients with anterior cruciate ligament deficiency (Chapter 5).

• To explore the relationships amongst subjective (self-perceived) measure of knee function (International Knee Documentation Committee [IKDC] knee evaluation form, a primary outcome measure of the thesis) and objective measures of function (single-leg hop for distance [HOP]), musculoskeletal (anterior tibio-femoral displacement [ATFD; knee laxity]) and neuromuscular performance (peak force [PF, strength], rate of force development [RFD], electromechanical delay [EMD], force-error [FE]), at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery (Chapter 6).
**Thesis Questions**

These thesis aims pose the following questions [Table 1.1].

<table>
<thead>
<tr>
<th>Thesis Question</th>
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<tr>
<td>i) Is there evidence that NCON rehabilitation improves self-perceived functional responses as measured by IKDC, KOOS and PP following ACL rehabilitation compared to traditional CON practice?</td>
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<tr>
<td>ii) Is there evidence that NCON rehabilitation improves objectively-measured outcomes of functional (HOP), musculoskeletal (ATFD) and neuromuscular performance (PF, RFD, EMD and SMP) following ACL rehabilitation compared to traditional CON practice?</td>
</tr>
<tr>
<td>iii) Are there relationships amongst the subjective measure of knee function (IKDC) and objective measures of function (HOP), musculoskeletal (ATFD) and neuromuscular (PF, RFD, EMD and SMP) performance at pre-surgery and 24 weeks post-surgery and amongst the change score between pre-surgery and 24 weeks post ACL reconstructive surgery?</td>
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**Table 1.1  Research questions posed.**

The questions upon which this thesis is based are addressed by the randomised control study (RCT) presented in Chapters 4 and 5, and by evaluating the relationships of selected indices in Chapter 6. Chapter 7 discusses the complete thesis and contextualises the answers. In addition, a summary of the applicable key findings, together with the study limitations, recommendations for future research and the possible clinical implications that this thesis has generated are presented.

The following Chapter reviews the literature and thus provides the background for this thesis (Chapter 2). The general methods demonstrated in the RCT and relationship evaluation investigations (Chapter 4, 5 and 6) are described in Chapter 3.
Chapter 2:

Literature Review
Chapter 2: Literature Review

The following chapter describes the structural anatomy and histology of the anterior cruciate ligament (ACL) and how this plays a role in knee joint stability. Evidence regarding the incidence and potential mechanisms of injury are reviewed, particularly in relation to a proposed model of knee joint stability. The current concepts of rehabilitation and the efficacy of current practice following ACL reconstruction surgery are presented. The importance and relevance of minimally detectable change (MDC) and the potential difficulty in determining minimal clinically important difference (MCID) in ACL-related practice is identified. The reliability and reproducibility of selected indices of subjectively- (self-perceived) and objectively-measured outcomes of function together with musculoskeletal and neuromuscular performance are examined and discussed.

A formal systematic literature review of concurrent versus non-concurrent training/conditioning is strategically appraised and the associated conceptual theory of the interference effect/phenomenon is described.

2.1 Anatomy of the anterior cruciate ligament

The orientation of the anterior cruciate ligament (ACL) is like a hand in a trouser pocket, lying obliquely. It originates from the medial side of the lateral femoral condyle and runs anteriorly and medially through the intercondylar notch, as it fans out and attaches distally to the medial tibial eminence (Zantop et al. 2005). The ACL has a broad oval footprint on the tibia, 11mm in the coronal plane and 17mm in the sagittal plane (Zantop et al. 2005, Duthon et al. 2006). Part of the ACL attachment on to the tibia has also been reported to
blend into the anterior horn of the lateral meniscus (Zantop et al. 2005). The ACL is oval in diameter according to Zantop et al. (2005); however Duthon et al. (2006), describes the cross-sectional shape as irregular and cannot be described by any simple geometric form. It is narrower mid-substance and the ACL has been reported to be 3.5 times larger at its insertions and the tibial insertion is approximately 120% that of the femoral (Zantop et al. 2005). The ACL width ranges from 7mm – 12mm and is significantly larger in men (Zantop et al. 2005).

The ACL is made up of two bundles of dense connective tissue inside a membranous synovial sheath (Johansson et al. 1991a and 1991b, Zantop et al. 2005). The two distinct bundles are referred to as the anteriomedial (AM) bundle and the posteriolateral (PL) bundle. The AM bundle originates from the most anterior and proximal aspect of the femoral origin and inserts at the anteriomedial aspect of the tibial insertion (Duthon et al. 2006). The PL bundle originates from the posteriolateral aspect of the femur and inserts into the posteriolateral aspect of the tibial attachment (Duthon et al. 2006). The ACL bundles are not isometric and their lengths vary depending on the tension placed across the ligament at different joint angles. In flexion the ACL becomes more horizontal as the AM bundle tightens and spirals around the easing PL bundle (Zantop et al. 2005). At 30° and 90° of knee flexion the AM bundle tightens and has been reported to lengthen by 5% and 12%, respectively, and the PL bundle loosens, shortening by 14% and 32%, respectively (Duthon et al. 2006). In full knee extension, the PL bundle is tight and reported to measure 22.5mm in length and the AM bundle relatively lax measuring 34mm (Duthon et al. 2006). In addition, the PL bundle contributes more to rotational stability of the knee than the AM bundle (Zantop et al. 2005). As the knee internally
rotates, the PL bundle lengthens and tightens more so than external rotation, most noticeably at 30° knee flexion (Duthon et al. 2006). It should be noted from approximately 30° to near full extension is when ACL injuries are most likely to occur (Renstrom et al. 2008, Alentorn-Geli 2009).

Histologically, there are three distinguishable zones; proximal, middle and distal. The proximal aspect consists mainly of fusiform fibroblasts, Type II collagen and glycoproteins, whereas the mid portion contains fusiform and spindle shaped fibroblasts and has a higher density of collagen. The mid part of the ligament also includes elastic fibres which can absorb stress and oxytalin fibres which can withstand moderate multidirectional stress. In comparison, the distal tibial portion has a relatively low density of collagen bundles and this end of the ligament is the most solid and containing chondroblasts and ovoid fibroblasts (Duthon et al. 2006).

The blood supply to the proximal ACL is supplied by vessels from the middle genicular artery and the distal ACL by branches of the lateral and geniculate artery (Johansson et al. 1991a and 1991b, Zantop et al. 2005, Duthon et al. 2006). The distribution of blood vessels within the ACL is not homogenous (Duthon et al. 2006). Avascular areas exist at the ACL insertions, predominantly distally and areas within the ligament where chondrocyte-like cells appear (Zantop et al. 2005, Duthon et al. 2006).

Neural innervations of the ACL are within the subsynovial sheath and at the insertions and are supplied by the posterior articular branches of the tibial nerve. Most of the nerves are associated vasomotor function. However, other smaller myelinated and unmyelinated nerves have been found in the fascicles of the ligament and have a role in proprioception and therefore possibly contribute to the dynamic stability of the knee (discussed in Section 2.3).
include Golgi-like receptors and Vater-Pacini receptors found at the proximal and distal portions of the ACL which are sensitive to tension and rapid movements. Ruffini receptors are sourced predominantly at the proximal superficial portion of the ACL and these are sensitive to stretching (Johansson et al. 1991a and 1991b, Duthon et al. 2006). In addition, these nerves are associated with a phenomenon called the “ACL reflex” where their activation affects motor activity of the muscles around the knee. It is suggested that this reflex is too slow to protect the knee at a point of injury, but it might be associated with loss of muscle strength following ACL injury (Krogsgaard et al. 2002, Duthon et al. 2006).

The anatomy of the ACL in part explains its role in the function and stability of the knee. The primary role of the ACL is to control anterior translation of the tibia on the femur (Johansson 1991a and 1991b). In fact, the ACL provides an average anterior restraint of 82% – 89% at 30º knee flexion and 74% – 85% at 90º knee flexion (Duthon et al. 2006). The major secondary role of the ACL is to act as a restraint to internal rotation during the terminal stages of knee extension (Duthon et al. 2006). Therefore, when the ACL is ruptured, it can lead to functional instability of the knee and increases the risk of further injury (Lohmander et al. 2004, Beynnon et al. 2005, Renstrom et al. 2008, Alentorn-Geli 2009).

The following section (2.2) discusses the incidence and mechanism of ACL injuries and the efficacy of rehabilitation.
2.2 Anterior cruciate ligament injury

2.2.1 Epidemiology

The 2012 Olympics’ legend was “Inspire a generation”. The benefits derived from sport and exercise are well known. A current government initiative is to improve society’s activity in order to try and tackle obesity (NICE.org.uk), and lessen the knock-on demands this has on the NHS, such as earlier onset of osteoarthritis of weight-bearing joints. This plan runs along-side current and controversial cuts to services within the NHS. Therefore, now more than ever, it is of uppermost importance to prevent injury or rehabilitate from injury in the most efficient and cost effective way.

Sporting injuries in the youth are a public health concern and the knee joint is reported to be the most common and most severe with an associated high economic cost to the individual and to society (Louw et al. 2008). This concern led to the first systematic review of the literature regarding epidemiology of knee injuries among adolescents (Louw et al. 2008). Though this review declares limitations of reliability and validity, it does suggest that knee injuries constitute a significant proportion of the injuries sustained worldwide, particularly in females.

In addition, a prospective epidemiological study by Dallalana et al. (2007) examined 546 players from 12 English Professional Rugby Union clubs over two seasons. The study revealed medial collateral ligament injury, together with chondral/ meniscal and anterior cruciate ligament (ACL) injuries were among the injuries of highest risk among all injury types in English professional rugby union. Furthermore ACL injuries accounted for 2 – 3 retirements and led to the largest proportion of missed days.
In a classification of 1,833 knee injuries, Bollen et al. (2000) found 40% were ligamentous and of the 500 ligament injuries 46% were identified as ACL and a further 13% combined ACL and MCL. Bollen et al. (2000) states that any district general hospital with a population catchment of 400,000 can expect approximately two fresh ACL injuries per week presenting to their casualty department, requiring treatment and rehabilitation.

However, not all ACL injuries will need reconstructive surgery (Beynnon et al. 2005, Di Stasi et al. 2012). Following ACL injury patients can be categorised as ‘copers’ or ‘non-copers’. Copers can often overcome incidences of instability by modifying their lifestyle or demonstrate better neuromuscular control and or show better adaptation to rehabilitation and training compared to non-copers (Beynnon et al. 2005, Di Stasi et al. 2012). Or it might be inadvisable for the patient to undergo reconstructive surgery due to other pathologies or medical reasons (Beynnon et al. 2005). Despite this, between 2011 - 2012 a nominal ≥250 ACL reconstructions were performed at RJAH Orthopaedic and District NHS Foundation Trust at an average cost of up to ≥£3,000. In addition, each of these patients required a minimum of 6-months rehabilitation, consisting of approximately ≥18 hours with an estimated cost of ≥£500. Therefore, more efficient rehabilitation might provide cost savings to the patient in terms of time out of work/ sport/ logistics, but also to society and the NHS.

In order to devise an efficacious rehabilitation guide it is important to understand mechanisms of injury and to prevent future injuries. The following section (2.2.2) describes the aetiology of ACL injury.
2.2.2 Aetiology

A review by Renstrom et al. (2008) presents the Olympic committee’s current concepts on non-contact ACL injuries in female athletes. It divides the risk of such injuries into external and internal risk factors.

External factors include competition in games versus practice, footwear, terrain, protective equipment and weather. In examining these factors very little evidence could be found regarding the effect of playing surface, sport-specific factors, age, athleticism, skill or psychological characteristics prior to injury. Internal risk factors are listed as biomechanical alignment, ACL geometry, bony congruency and hormone levels. Any of these factors might play a part in increasing the risk of injury (Griffin et al. 2006, Renstrom et al. 2008) [Figure 2.1].
Almost 80% of all ACL injuries occur during non-contact rotational, pivoting and twisting type manoeuvres, landing from a jump or hop, or the sudden deceleration from a sprint. The ACL ruptures as anterior translation of the tibia and dynamic valgus movement occurs near full extension and is similar to the compromised movement pattern illustrated in Figure 2.2. Quadriceps’ dominance and possibly increased gastrocnemius’ activity has been indicated as a possible cause for this sequence along with potential neuromuscular imbalances. This can be compounded as all the body’s weight is placed on the foot outside of the centre of gravity as the trunk rotates (Renstrom et al. 2008).
Figure 2.2 Adapted photograph from Renstrom et al. (2008) demonstrating both the ideal and compromised biomechanics during a single leg squat. This compromised movement pattern might facilitate ACL injury during dynamic tasks.

The purpose of a recent review by Alentorn-Geli (2009) was to sequence the potential mechanisms and risk factors for non-contact ACL injuries in soccer players. It was noted that this population is at higher risk of ACL injury relative to other sports and that most of the ACL injuries sustained are non-contact in nature. The review concluded that the mechanism for non-contact ACL injury was multi-factorial and included manoeuvres such as changing direction and cutting combined with deceleration, landing from a jump and pivoting, all performed with the knee in near extension and with the foot fixed. All of these movement patterns could involve any combination of knee valgus, varus,
internal rotation and external rotation moments and anterior tibial translation force. The latter might be the most detrimental isolated force with the other moments adding to the strain. The risk factors were found to be dry weather conditions, artificial turf, possibly an increased body mass index (BMI), generalised joint laxity, small or narrow intercondylar notch width, size and strength of the ACL, pre-ovulatory phase of the menstrual cycle in females not using oral contraceptives, sex hormones, decreased (relative to quadriceps) hamstring strength and recruitment, muscular fatigue altering neuromuscular control, decreased ‘core’ strength and proprioception, low trunk, hip and knee flexion angles and high dorsiflexion at the ankle when performing sporting tasks, lateral displacement and hip adduction combined with increased knee abduction moments, increased hip internal rotation and tibial external rotation. The exact role of the pelvis and trunk remains unknown and further study is suggested. In addition, this review also found limited evidence to support that an increased Q-angle (a static measure of the angle formed by a line directed from the anterior-superior iliac spine and from the central patella to the tibial tubercle) is a risk factor in non-contact ACL injuries in soccer players.

Therefore, establishing the potential causative factors of injury to the ACL have led to the development of prevention and rehabilitation programmes with a neuromuscular emphasis. Hewitt et al. (2006) performed a meta-analysis of neuromuscular interventions aimed at injury prevention and concluded there was evidence to suggest neuromuscular training decreases the risk factors of ACL injury and therefore decreases the incidence of ACL injuries. The advice from this analysis is that every injury prevention programme should include plyometrics, balance and that strengthening exercises and this type of training should be administered more than once a week for a minimum of 6 weeks.
A further meta-analysis evaluating the effectiveness of neuromuscular training to reduce ACL injury by Sugimoto (2012) discusses the potential benefits of cognitive and physical perturbation training (including plyometric drills, and one-legged balancing exercises). The results show neuromuscular studies specifically aimed at ACL injury prevention in females found a relative risk reduction of 73.4% in non-contact ACL injuries and 43.8% in contact ACL injury. This type of training has also shown reductions in other knee and ankle injuries and improvements in performance (Sugimoto 2012). Both of these training models are very similar to the latter phases of the traditional rehabilitation guidelines administered during the RCT presented in this thesis [refer to Appendix A – RJAH anterior cruciate ligament rehabilitation guide].

It is advisable that ACL rehabilitation should include an element of neuromuscular training. The importance of neuromuscular control and dynamic stability is reviewed in the following section.

2.3 Model of knee joint stability

Passive stability of the knee is provided by osseous and meniscal congruency and ligamentous and capsular restraints (Johansson 1991a and 1991b, Blackburn et al. 2009). The components of dynamic loading and thus, the dynamic stability of the knee include the central nervous system, neuromuscular and musculoskeletal factors and their complex interplay (Huston and Wojtys 1996, Griffin et al. 2005, Blackburn et al. 2009). Figure 2.3 demonstrates a schematic of one proposed model.
Following ACL injury there are changes in kinematics, kinetics and neuromuscular activity (Roberts et al. 2000, Gruber et al. 2004, Griffin et al. 2005, Myer et al. 2005, Roberts et al. 2007, Renstrom et al. 2008, Ristanis el al. 2009, Angoules et al. 2011, Krogsgaard et al. 2011). This can result in recurrent ‘giving way’ of the knee joint particularly in twisting and turning (Renstrom et al. 2008). A possible factor contributing to knee joint instability was suggested by Myer et al. (2005). This study found differences in EMG firing patterns between male and females during a potentially injury threatening manoeuvre. The quadriceps firing was described as ‘unbalanced’ giving rise to a dynamic valgus force and potentially increasing the risk of ACL injury. This is similar to the compromised movement patterns described by Renstrom et al. (2008) [Figure 2.2]. Hence, the work by Griffin et al. (2005) is of great clinical interest, as it concludes that the central nervous system can learn behaviours

**Figure 2.3** A proposed conceptual model of knee joint stability.
and patterns of movement which can in turn react to ‘at risk’ positions and manoeuvres.

Neuromuscular factors include rate of force development, electromechanical delay, motor recruitment response, coordination of movement and proprioception (Huston and Wojtys 1996, Gruber et al. 2004, Roberts et al. 2007, Blackburn et al. 2009, Minshull et al. 2009, Ristanis et al. 2009, Krogsgaard et al. 2011, Gokeler et al. 2012). Rate of force development is determined as the slope in the force-time curve and indicates the capability for delivering explosive strength (Gruber et al. 2004, Minshull et al. 2009, Hannah et al. 2012). Higher rates are thought capable of stiffening joint complexes quickly and thus prevent injury (Gruber et al. 2004, Ristanis et al. 2009). It is has been suggested that proprioceptive enhancement of neural activation might have a positive influence on the stretch-shortening cycle, increasing the rate of force development (Gruber et al. 2004). Electromechanical delay is often used to characterise neuromuscular function and is defined as the time interval between the onset of electromyographic (EMG) activity and force production (Zhou et al. 1995, 1996, Blackburn et al. 2009, Minshull et al. 2007, 2009, Hannah et al. 2012). The decrease in electromechanical delay will increase the rate of force development and this equilibrium is thought to be critical in dynamic joint stability (Blackburn et al. 2009). In addition, electromechanical delay has been suggested as revealing the true effectiveness of muscles to provide a mechanical response and protection in real-life situations (Ristanis et al. 2009). The majority of studies have shown no difference in EMD across genders (Minshull et al. 2007, Blackburn et al. 2009, Hannah et al. 2012). However, Blackburn et al. (2009) suggests longer EMD times are found in females and this might contribute to
the higher incidence of ACL injuries. Electromechanical delay is influenced not just by injury and subsequent surgery, but also by the graft choice used in ACL reconstruction. For example, a controlled case study by Ristanis et al. (2009) found significant elongation in EMG values in the hamstrings where a Semitendinosus/ Gracilis graft had been used, even at two years post-surgery.

Interestingly, Krogsgaard et al. (2011) found the reinnervation of the ACL graft following reconstruction was compromised even up to 12 years following surgery. Consequently, this might affect joint proprioception. In addition, Roberts et al. (2000) found patients with unilateral ACL reconstructions to have bilateral proprioceptive deficits compared to healthy control subjects. However, there remains no standard test for knee joint proprioception/ sensorimotor control. (Roberts et al. 2000, Roberts et al. 2007). Furthermore, a recent systematic review by Gokeler at al. (2012) found that proprioception had a low to moderate correlation with knee joint function following ACL reconstruction. This alludes to the possibility that proprioception might only have limited clinical relevance in assessing function. However, this study highlighted the lack of unified sensorimotor testing. Although most studies examined joint position sense or threshold to detect passive movement, none investigated force-reproduction at a knee angle associated with a high incidence of injury as presented in this thesis. Gokeler at al. (2012) urges the development of new tests to determine the relevant role of the sensorimotor system.

Furthermore, the lack of correlation between proprioception and other functional outcomes could probably in part be due to the complexity of proprioception as it encompasses both spinal and cortical projections and reflective pathways (Roberts et al. 2007). In addition, the ability to consciously
perceive sensorimotor signals may differ for each individual and could be dependent on many factors (Roberts et al. 2007).

When establishing the time frame required to restore sensorimotor performance following ACL surgery, Angoules et al. (2011) found that maximum proprioception was established 6 months post-surgery (irrespective of the autologous graft used). The authors suggest this amount of time is required for the graft to re-vascularise, re-innervate and remodel.

The following section provides a review of the current literature regarding how, when and what type of training is advised following ACL surgery.

2.4 Rehabilitative interventions

2.4.1 Post-operative anterior cruciate ligament reconstruction rehabilitation

A review by Manske et al. (2012) cited 113 studies which examined recent advances in rehabilitation following ACL reconstruction and concluded that in order to return the patient to full function, (s)he must have full terminal knee extension, optimal motor control of the quadriceps, full neuromuscular control, strength and endurance of the affected limb. In addition, it was advised rehabilitation should be based on clinical science and the best available evidence. The authors suggest a post-operative programme based on the healing process ('ligamentisation') of the graft. The programme is separated into 5 phases. Phase I covers week 1 - 4 and is largely based around protecting the graft, controlling/ minimising inflammation, regaining extension and education. Phase II is the shortest phase, week 4 - 6 and aims at restoring normal gait and increasing range of movement. From week 6 - 3 months,
Phase III commences targeting strength, endurance, proprioception and preparation for functional activities. Phase IV continues to advise progression to 6 months and focuses on strength, power, proprioception and controlled individual functional activities/sport. It isn’t until beyond 6 months that full return to sport is advised. This guide is similar to the traditional programme used as the control in this thesis; however, unlike Manske et al. (2012), no functional knee brace was provided [Appendix A – RJAH anterior cruciate ligament rehabilitation guide]. This was in agreement with systematic reviews by van Grinsven et al. (2010) and Lobb et al. (2012), where results from both reviews found no strong evidence to support the use of bracing as an adjunct to post-operative rehabilitation. These reviews do not claim to be exhaustive and Lobb et al. (2012) states there is limited evidence for many other interventions including delayed and accelerated rehabilitation, which would require further investigation.

The emphasis in the majority of rehabilitation guides is to restore full physical function; few discuss the psychological factors (Doyle et al. 1998, Brewer et al. 2007, Ardern et al. 2012). A systematic review by Ardern et al. (2012) scrutinised eleven studies, evaluating 983 athletes and included 15 psychological factors associated with returning to sport following injury. Not surprisingly, positive psychological responses appear to promote a greater likelihood of the athlete returning to their pre-injury level of performance. Fear was found to be the most common factor that would hold an athlete back from full function. Therefore, it is suggested that goal setting and other confidence building strategies should be incorporated in rehabilitative programmes. It is advised that clinicians should utilise validated and condition-specific measures in assessing psychological factors in order to identify the risk of developing
abnormal psychological behaviours (Ardern et al. 2012). Doyle et al. (1998) suggests the use of performance profile techniques based on the principles of personal construct theory, as an assessment and measurement tool.

Goal setting is frequently included in standard clinical practice where the physiotherapist sets rehabilitation goals with the patient. However, although this is documented in the clinical notes, it is not usually formalised and measured in a standardised way.

Often strength is assessed and used as an indicator for a successful rehabilitative outcome. Eitzen et al. (2008) provides evidence from a cohort study proposing that pre-operative rehabilitation should emphasise quadriceps muscle strength as deficits in quadriceps muscle strength of less than 20% of the uninjured limb before ACL reconstruction, reduce the severity of longer term post-operative deficits. This level of parity is also suggested by Thomeé et al. (2011).

The indication for ACL reconstructive surgery is instability that cannot be overcome by conservative measures and/or where modification of lifestyle is not appropriate or acceptable. The most common autografts used in ACL reconstruction are patella tendon, commonly referred to as bone-patella tendon-bone (BTB), or hamstring tendon (Gracilis and Semitendinosus). The graft selection process used in the RCT presented in this thesis was based upon the clinical decision of the surgeon, following an informed discussion and consent of the patient.

A recent study by Moisala et al. (2007) reviewed 48 patients, whose ACL-deficient knees were reconstructed between 1997 and 2000 using a BTB or a hamstring graft. It found no significant strength deficits between BTB and Hamstring groups. However, in the long-term the BTB patient group
demonstrated greater quadriceps strength compared to the patients with hamstring grafts. In addition, the BTB patient group had increased knee stability and less knee flexion torque deficits. In accordance with this study, the rehabilitation programme used for the RCT presented in this thesis was the same for both types of autologous tendon graft used.

Neuromuscular factors including muscle endurance, strength and activation pattern have a positive role in the ability to prepare and anticipate risky movements such as cutting and changing direction at speed (Griffin et al. 2005). Fundamentally, rehabilitation aims at addressing these factors and movement patterns in order to restore full function in the speediest, most effective and efficient way. The rehabilitation guide patients followed during the RCT presented in this thesis has been described in Appendix A – RJAH anterior cruciate ligament rehabilitation guide. It incorporates all the current evidence on ACL rehabilitation and traditionally, it is applied in a concurrent format.

The following section investigates how efficacy of ACL rehabilitation is currently measured.

2.4.2 Assessment of efficacy of anterior cruciate ligament rehabilitation

The criteria for establishing the efficacy following anterior cruciate ligament (ACL) reconstruction surgery is varied. van Grinsven et al. (2010) examined 32 randomised control trials and reviews of rehabilitation following ACL reconstruction and found the criteria for efficacy ranged from visual analogue scores for pain, circumference measurements for swelling and handheld goniometer devices for range of movement. The latter have been used to assess parity of performance between limbs. Differences in contralateral leg
strength for quadriceps and hamstrings and the quadriceps: hamstrings ratio are common in assessing whether return to sport is advisable (Alentorn-Geli 2009, Renstrom et al. 2008, van Grinsven et al 2010). It has been reported that quadriceps and hamstring strength should be within 15% of the contralateral limb (Eitzen et al. 2008, van Grinsven et al 2010, Thomeé et al. 2011). In addition, hop tests and comparison to the contralateral side aiming for >85% parity is widely applied (Clark 2001, Gustavsson et al. 2006, van Grinsven et al. 2010). The patients’ perceived tolerance to sport-specific activity and International Knee Documentation Committee score forms have also been administered to judge efficacy (Hambly et al. 2010, van Grinsven et al. 2010, Collins et al. 2011, Irrgang et al. 2012).

Möller et al. (2009) reports long-term follow-ups (at 2 years and at ≈11.5 years) on the quality of life of 56 patients following ACL reconstruction using knee laxity, knee flexor and extensor strength, hop for distance, Lysholm, Tegner activity scale, Knee Injury Osteoarthritis Outcome Score (KOOS) and SF-36 health survey. Though the study reported good knee function, it could not isolate any measure as a predictor for long-term outcome.

Hewitt at al. (2006) described a combination of pre-season and in-season neuromuscular ACL injury prevention training programmes undertaken by athletes (involving plyometric, balancing, core stability, strengthening exercises, alongside feedback on biomechanical control during dynamic tasks) and reported that this style of training was efficacious. This type of neuromuscular training is similar to the end-phase post-operative ACL rehabilitation programme followed in the RCT presented in this thesis [Appendix A]. The authors also describe the difficulty in assessing cost in relation to training and the potential for reduction of ACL injury. No study was found
during the completion of this thesis that assessed the cost effectiveness of post-operative ACL rehabilitation with respect to the NHS. Yet, it would be reasonable to assume that a speedier recovery to function and potential reduction of further injury might reduce costs to the NHS and to the patient.

However, it is recommended that further long-term evaluation, with respect to ACL rehabilitation and injury prevention programmes, are required to address their efficacy (Hewitt at al. 2006, Lohmander 2004).

Establishing the minimally detectable change and potentially, the minimal clinically important difference, also plays a role in determining efficacy and is discussed in the next section.

2.4.3 Determining minimally detectable change and minimal clinically important difference

Results from research trials often show statistically significant outcomes. However, a clinical setting requires these outcomes pertain to a meaningful clinical difference. A clinically important difference represents a change that would be considered substantial and worthwhile, in that the patient would undergo the intervention again, given the choice. The minimal clinically important difference (MCID) is the lowest threshold value for this decision (Jaeschke et al. 1989, Copay et al. 2007, Revicki et al. 2008). In addition, patient populations suffering different pathologies might have different MCIDs for the same outcome measure. Calculating a MCID is a challenge as currently there is no consensus regarding the best method (Jaeschke et al. 1989, Copay et al. 2007, Revicki et al. 2008).

Identifying MCID can be quite difficult as they are all instrument-dependent. Copay et al. (2007) and Revicki et al. (2008) reviewed the various
definitions and methods used to determine MCID. Both authors describe two approaches in measuring a quantifiable change in outcome and depending on the type of change to be measured, these are anchor-based methods or distribution-based methods.

The four anchor-based methods compare the change in a self-perceived/patient-reported/subjective outcome score to some other measure of change acting as an external criterion, for example clinical end points, patient-rated global improvement, other self-perceived outcome scores or any combination of these. It is important that the external criterion should also have some correlation to the patient-reported outcome to establish MCID (Walters and Brazier 2005, Revicki et al. 2008). The external criterion is chosen depending on relevance to the investigation and its validity. The first method compares self-perceived ‘within patients’ score changes to an external criterion. The MCID for this approach was considered to be the average change of the patients who exhibited small changes or the mean change in scores of the ‘most improved’ patients. The second method is the ‘between-patients’ score change, where groups of self-perceived outcome scores are compared to an external criterion and the MCID is the minimum difference between two adjacent levels of scales. ‘Sensitivity and specificity-based’ approach is the third method, suggesting that a score which best discriminates between groups of patients is used as the MCID. Finally, the least-used approach is described as ‘social comparison’, whereby patients compare themselves with other patients and the MCID is identified as the difference in scores who rate themselves as “slightly better” or “slightly worse” instead of “about the same” as compared to their counterpart (Copay et al. 2007, Revicki et al. 2008).
Distribution methods are used to support and help interpret the estimates from the anchor-based methods or used if anchor-based methods are unavailable (Revicki et al. 2008). These methods compare change in a self-perceived outcome score to a measure of variability, for example standard error of measurement (SEM), standard deviation (SD), effect size or the minimum detectable change (MDC). The authors suggest 1 SEM or 0.5 SD (which is equivalent to 1 SEM with a reliability of 0.75) could be used as a ‘yardstick’ for determining MCID. The MDC is related to SEM and is considered to be the smallest difference above the measurement of error at a given confidence level, thus the MCID should be at least equal or greater than this (Jaeschke et al. 1989, Walters and Brazier 2005, Copay et al. 2007, Revicki et al. 2008). These distribution methods can be used to support and help interpret the estimates from the anchor-based methods.

Therefore, it is apparent that the better the reliability of a research outcome measure, the better its MDC and this facilitates the determination of MCID (Revicki et al. 2008). However, in order to have confidence in MCID and its precursors, multiple measurement replicates across multiple research trials would be needed (Revicki et al. 2008).

The authors of these reviews duly point out the limitations to these methods, for example, each method produces a different value. In addition, the balancing of cost implications against the benefits of change should be considered. Furthermore, the patient-related scores are dependent on the initial status or baseline of the patient. If several anchors are used a range of MCIDs will result; for example Kosinski et al. (2000) defined MCID for a population of rheumatoid patients as 1% - 20% improvement in the extent of swelling within a
joint. Ultimately there is no agreed upon method to calculate MCID and it can only really be ‘estimated’ (Copay et al. 2007, 2008, Revicki et al. 2008).

The following section reviews various outcomes methods that have previously been used to establish measurement reproducibility and reliability, or to measure effects following ACL surgery. Where there is evidence in the literature, MDC and MCIDs are reported.

2.5 Self-perceived (subjective) outcome measures

‘Self-perceived measure’, ‘subjective score’, ‘patient-reported outcome’ are interchangeable terms frequently used to describe how a patient rates his/her level of ability or symptoms. These outcome measures score the patient’s response to questions or statements about their levels of activity, symptoms, mood and general health for example (Revicki et al. 2008). These responses are then calculated to provide a score. When the self-perceived outcome is utilised a number of times the change in score has been referred to as a minimal detectable change (MDC). As mentioned in the previous section, MDC can then be used to assist in the estimation of MCID.

There are three main reasons according to Copay et al. (2007), why self-perceived outcomes are used in research.

1. The patient may be the only source of the information and the effects of the intervention can only be judged by them. This might be pain or fear for example, where no adequate objective measure exists.
2. The lack of correlation between objective and subjective data.
3. There is no third-party bias.

The following subjective assessment methods have been reported to pertain to knee specific problems.
2.5.1 International knee documentation committee (IKDC) subjective knee evaluation form

The International Knee Documentation Committee (IKDC) subjective score form is comprised of 18 questions and scored in the range 1 – 100, where a score of 100 is optimal. It is specifically aimed at patients who have anterior knee pain, knee ligament, meniscal, chondral injury or pathology and where normative data is available and/or can be collected. The IKDC contains three domains; the first scores symptoms, the second scores sports and daily activities. However, the third domain comparing current to pre-operative knee function, is not calculated in the overall score. On average, it takes 10 minutes to complete the IKDC form and 5 minutes to administer and has a recall period of 4 weeks. No training is necessary to utilise the score form (Collins et al. 2011, Irrgang et al. 2012).

This score form was initially developed in 1987 when the International Knee Documentation Committee was created in order to devise and provide a knee-specific and standard method of detecting improvement or deterioration in symptoms, function and sporting activity experienced by the patients (Irrgang et al. 2001). The form was later revised in 1997 by the American Orthopaedic Society for Sports Medicine (AOSSM) board and evaluated for reliability and validity. At this time, the board found the IKDC test-retest reliability to range from 0.92 - 0.95. It was concluded that the IKDC is a reliable and valid knee-specific measure across mixed sex groups with various knee conditions. It has undergone minor revisions since, however the IKDC (2000) subjective knee evaluation form remains the current version (Collins et al. 2011) [Appendix B].

More recently, an AOSSM task force has provided a summary of outcome measures for sports-related knee injuries including the IKDC
subjective knee evaluation score form (Irrgang et al. 2012). The AOSSM task force review (2012) found that the IKDC demonstrates relationships with other similar measures and to measures of general physical and emotional function. This is in agreement with findings from a previous review by Collins et al. (2011), suggesting that the construct validity of the IKDC is demonstrated via strong correlations with other subjective scores; the Short Form 36 (SF 36), the Cincinnati Knee Rating System, the visual analogue for pain, Oxford 12 questionnaire, Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) and the Lysholm score. However, Collins et al. (2011) suggests that the lack of item contribution by patients and the subsequent minor revisions means that its content validity should not necessarily be assumed. The internal consistency for the IKDC is reported as $\alpha = 0.77 \text{–} 0.97$ and interclass correlation coefficient test-retest reliability ranges from $0.87 \text{–} 0.98$ (Irrgang et al. 2012). Effect sizes over time, relating to the response of the inventory, have been shown to range from $0.76 \text{–} 2.11$ (Irrgang et al. 2012). The larger effect sizes are seen predominantly from 6 months post-surgery in ACL populations (Collins et al. 2011). Minimal detectable change has been shown to vary from $6.7 \text{–} 20.5$ and minimal clinically important difference also encompasses a large range $3.19 \text{–} 16.7$ (Collins et al. 2011, Irrgang et al. 2012).

In summary, the IKDC addresses items which are important to patients. It offers adequate internal consistency for mixed groups with various knee pathologies and requires minimal administrative time. However, its validity cannot be assumed, the relatively long recall-period may be problematic to some patients and it might be unreliable for assessing patients on an individual basis (Collins et al. 2011).


### 2.5.2 Knee injury and osteoarthritis outcome score (KOOS)

The Knee Injury and Osteoarthritis Outcome Score (KOOS) was developed as an extension of the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) to address problems associated with arthritis as well as injury to the knee (Roos et al. 1998, Lohmander et al. 2004, Collins et al. 2011). This is pertinent to the ACL population, because following a serious knee injury such as an ACL rupture, patients have a higher risk of developing osteoarthritis (Lohmander et al. 2004).

The KOOS inventory is used to evaluate knee symptoms and function over a short term (1 week) and a long term (decades) (Roos et al. 1998, Lohmander et al. 2004, Collins et al. 2011). Since its development in 1995 by Ewa M Roos and colleagues, the KOOS remains unchanged [Appendix C] (Roos and Lohmander 2003). It contains 42 items separated over five domains; pain, symptoms, activities of daily living (ADL), sport and knee related quality of life (QOL). Each of the dimensions are scored separately and then transformed to a 0 – 100 score, where 100 would suggest there are no problems with the knee at all. On average, it takes 10 minutes to complete, 5 minutes to administer and has a recall period of one week.

In the initial development of the KOOS score, patients were directly involved, thus providing content validity. Collins et al. (2011) reports strong correlations between KOOS, Short Form 36 (SF 36) and Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), demonstrating construct validity. Internal consistency, test-retest reliability, effect size, and minimal detectable change have been reported for each of the 5 dimension within the KOOS score and are outlined in Table 2.1 (Irrgang et al. 2012). Roos and Lohmander (2003) suggest 10 points as a cut-off representing clinical significant
difference. However, recent literature disputes MCID stating, minimal clinically important difference has not been reported to date (Irrgang et al. 2012).

<table>
<thead>
<tr>
<th></th>
<th>Symptoms</th>
<th>Pain</th>
<th>ADL</th>
<th>Sports</th>
<th>QOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal consistency</td>
<td>α = 0.25</td>
<td>α = 0.65</td>
<td>α = 0.78</td>
<td>α = 0.84</td>
<td>α = 0.64</td>
</tr>
<tr>
<td></td>
<td>0.83</td>
<td>0.94</td>
<td>0.97</td>
<td>0.98</td>
<td>0.90</td>
</tr>
<tr>
<td>Test-retest reliability</td>
<td>R1 = 0.74 – 0.95</td>
<td>R1 = 0.80 – 0.92</td>
<td>R1 = 0.73 – 0.94</td>
<td>R1 = 0.45 – 0.89</td>
<td>R1 = 0.60 – 0.95</td>
</tr>
<tr>
<td>Effect Size</td>
<td>0.72 – 1.63</td>
<td>0.82 – 2.59</td>
<td>0.67 – 2.25</td>
<td>0.90 – 1.31</td>
<td>1.15 – 2.8</td>
</tr>
<tr>
<td>Minimal Detectable Change</td>
<td>9.9 – 24.3</td>
<td>11.8 – 29.0</td>
<td>11.9 – 31.5</td>
<td>12.2 70.0</td>
<td>14.2 – 34.0</td>
</tr>
</tbody>
</table>

Table 2.1  Table demonstrating the internal consistency, test-retest reliability, effect size, and minimal detectable change for each of the 5 dimension within the KOOS score (Irrgang et al. 2012).

The QOL subscale followed by Pain, are the most responsive, having the highest effect size, but this was in relation to total knee replacement, not ACL injury (Roos and Lohmander 2003). However, in a randomised control trial comparing two methods of ACL reconstruction, significant between-group differences were found in relation to ADL, Sport and QOL at various post-surgical time points (Roos and Lohmander 2003).

Roos and Lohmander (2003) state that the test-retest reliability is sufficient in most of the subscales to detect an individual’s change in performance over time.

Following the results of a Rach analysis, Comins et al. (2008) suggests caution when using KOOS as a score for ACL-reconstructed patients before they are 20-weeks post-surgery. This in part is due to the score form being devised to recognise arthritic symptoms predominantly.
However, a specific ACL-reconstructed athletic population studied by Salavati et al. (2011) at 7.6 ±2.2 months post-surgery, revealed KOOS to be reliable and valid. In addition, the utilisation of KOOS following ACL-reconstruction is a clinical recommendation and has been adopted by National Knee Ligament Registries (Hill and O’Leary, 2013).

2.5.3 Performance profile technique

Performance profiling is based on the principles of personal construct theory (Butler and Hardy, 1955). It is predominantly applied in sports psychology, whereby the athlete takes an active role in the process of identifying individual needs for training (Doyle and Parfitt, 1996, Doyle et al. 1998). By allowing the athlete to have an active role in the decisions made concerning their training and performance, and it is thought to increase motivation and compliance (Doyle et al. 1998).

A study by Doyle and Parfitt (1996) investigated the predictive validity of performance profiling in athletes. The process involved identifying ten to fifteen constructs by asking the athlete “what in your opinion are the qualities or characteristics of an elite athlete in your event?” The athlete was then asked to rate the constructs on a visual scale of 0 (not important at all) to 10 (of crucial importance). Subsequently, the athletes were asked to score “where do you rate yourself at the present time on each of the constructs you have listed?” 0 (could not be any worse) to 10 (could not be any better). Scoring was compared to the athletes’ actual performance and also to the coaches’ perception over three competitive athletic events. The results using a directional interpretation of the correlations, indicated a greater need (identified in the profile) was associated with an increased loss of performance and thus
providing predictive validity for the performance profile. Significant relationships were also found between coach-perception and profile discrepancy. In addition, coefficient of determination ($r^2 = 0.23 - 0.76$) suggested moderate psychometric utility of the performance profile. However, the results also indicate the performance profile might not be sensitive enough to detect small changes of performance in the elite athlete across a competitive season.

The construct validity of the performance profile was addressed by Doyle and Parfitt (1997). The completing of the profile was similar to that described in the predictive validity study by Doyle and Parfitt (1996), described above. The construct validity results showed that the constructs which the athlete determined as the most important, were the most sensitive and responsive to change and that any increase in actual performance was related to decreased need in the relevant construct. The authors suggest that the performance profile does show some construct validity, but it should not be used unreservedly, as it is unlikely to identify relatively small changes in performance and perceived need.

In populations where large changes in performance are expected, following ACL reconstruction for example, the limited ability of the performance profile to detect small changes might not be as crucial (Doyle et al. 1998).

In addition, performance profiles have been found to significantly correlate with important indicators of musculoskeletal performance, such as knee laxity and peak force, both prior to ACL-reconstructive surgery ($r = 0.68$ to 0.85) and 8 weeks subsequent to surgery ($r = 0.72$ to 0.82) (Gleeson et al. 2008). The strength of these relationships (explaining up to 72% of shared ‘objective-subjective’ variance) would suggest that the PP might be a viable alternative in comparison to traditional self-reported measures of knee function,
such as the IKDC or KOOS inventories. However, the longer-term efficacy of this technique during rehabilitation, has yet to be evaluated.

In addition, documenting what the patient perceives to be important factors required to establish normal function, might in turn increase the patient’s compliance to rehabilitation.

2.6 Objective outcome measures

2.6.1 Function – hop for distance

In a clinically based setting, functional performance tests are used to assess knee function and to determine when the patient is ideally suited to return to sport (Clark 2001, Hopper et al. 2002, Reid et al. 2007, Thomeé et al. 2011). The choice of functional performance test can depend on the population to be tested. When assessing ACL reconstructed patients, hop tests are predominantly used, comparing the injured with the contralateral uninjured limb (Clark 2001, Hopper et al. 2002, Reid et al. 2007, Thomeé et al. 2011). This type of test is popular as it requires relatively little space, it is meaningful to the patient and it does not depend on expensive equipment. Although it could be argued a hop test is not sport specific, it does mimic the forces encountered during most sports under controlled conditions (Clark 2001). In order to demonstrate a hop, it has been suggested that the patient requires sufficient flexibility, strength, rate of force development, power, proprioception, neuromuscular control, dynamic balance, agility and confidence (Clark 2001, Hopper et al. 2002). A hop test measures a cumulative effect of all of these variables and also those of joint laxity and pain (Clark 2001, Hopper et al. 2002). Thus, in the absence of sophisticated laboratory tests, hop for distance
is the preferred clinical assessment of lower limb function (Clark 2001, Thomeé et al. 2011).

In order to select a functional performance test, the clinician should be aware of the reliability and validity of the test to identify if the results are likely to be meaningful. Clark et al. (2001) addressed this issue by documenting a very detailed literature review of functional performance tests for an athlete with a knee ligament injury. Other researchers (Hopper et al. 2002, Reid et al. 2007) have presented similar intra-class correlation coefficients to those presented by Clark (2001). From the review of the literature, hop for distance was most applicable to the population examined in this thesis.

A summary of the results are detailed in the in the Figure 2.4.
Hop for Distance
*ICC 0.89-0.97 (Clark 2001)
*ICC 0.81 – 0.98 (Hopper et al. 2002)
*ICC 0.92: SEM ±3.49%: MDC ±8.09% (Reid et al. 2007)

Hop Battery (e.g. 6m timed, cross over, triple hop)
*ICC 0.97 (Clark 2001)

Vertical Hop
*ICC 0.97 (Clark 2001)

Practicality within clinical environment and post-surgical tolerance

Vertical Hop
Hop for Distance

Frequently used in the literature (Clark 2001, Reid et al. 2007, Thomeé et al. 2011).

Shuttle Sprint
*ICC 0.96 (Clark 2001)

Carioca
*ICC 0.96 (Clark 2001)

Two legged tests with rotational element offering some stress to dynamic stability/ACL function.

Two legged test offering general function not specific for instability/ACL function.

Vertical Jump
V% 7.7% (Risberg 1995)
ICC 0.93 – 0.99 (Clark 2001)

Jump for Distance
ICC 0.96 (Clark 2001)

Triple Jump
No reliability (Risberg 1995)
ICC 0.94-0.95 (Clark 2001)

Hop for Distance (HOP)

*ICC ACL specific populations

**Figure 2.4** Flowchart highlighting the decision process used to identify the objective measure of function used in this thesis; Hop for distance (HOP).
2.6.2 Anterior-posterior knee joint laxity – anterior tibiofemoral displacement

As previously discussed in section 2.1, the primary role of the ACL is to restrain anterior displacement of the tibia relative to the femur. Clinical assessment of anterior tibio-femoral displacement is often used not just to diagnose ACL injury, but also to establish the success of the ACL reconstruction surgery. In the absence of objective, instrumented equipment designed to measure ACL laxity, most clinicians use the Lachman’s Test. The Lachman’s Test has been shown to have superior accuracy in assessing abnormal anterior translation of the tibia compared to the Anterior Draw Test (Jonsson et al. 1982). This has been demonstrated in a meta-analysis by Scholten et al. (2003), who reviewed 17 studies. It was reported that both the pooled sensitivity and specificity data for the Anterior Draw to be 0.62 [95% confidence interval, 0.42 – 0.78] and 0.88 [95% confidence interval, 0.83 – 0.92], respectively, was inferior to that of the Lachman test (0.86 [95% confidence interval, 0.76 – 0.92] and 0.91 [95% confidence interval, 0.79 – 0.96]). This is the test used in the clinical settings when assessing a knee for anterior tibial translation, if an ACL injury is suspected.

The Lachman’s Test is performed with the patient relaxed in supine position, the knee is supported ≈15° knee flexion, the clinician stabilises the distal end of the femur with one hand, whilst exerting an anterior draw force on the proximal end of the tibia with the other hand. The clinician feels for the amount of displacement, but also the ‘end feel’ (Cooperman et al. 1990). The amount of displacement is graded from 0 – 3+. A score of 0 is given if there is no perceivable tibial translation, 1+ if up to 5mm is sensed in comparison to the uninjured knee, 2+ equates to 5 – 10mm and 3+ if the clinician feels there is
more than 10mm difference (Cooperman et al. 1990). “A solid end feel” describes a definite hard stop to the anterior translation of the tibia and suggests the ACL is in continuity, “a soft end feel” with no definite stop to the anterior translational stress, suggests complete rupture of the ACL (Cooperman et al. 1990).

Despite the popularity and clinical utility of this test, a study by Cooperman et al. (1990) demonstrated relatively poor intra-tester and inter-tester reliability for positive and negative judgements and the type of end feel. This study assessed two orthopaedic surgeons (with at least 15 years’ experience) and two physical therapists (with at least 5 years’ experience) that routinely used the Lachman’s test. Thirty two patients with unilateral knee injuries and no previous ACL surgeries were tested by all four clinicians. Thirteen of the 32 patients had sustained an injury to the ACL as diagnosed 6 weeks prior to the study via arthroscopy or arthrotomy. The clinicians were reminded of the grading scale prior to the examination.

All patients were randomly assigned and instructed to lie supine on a plinth where a sheet suspended from the ceiling at the level of the patient’s torso to prevent the clinician from recognising the patient. A researcher acted as a recorder and informed the clinician which was the non-injured knee. There was no discussion between the patient and the clinician.

The clinician tested the non-injured knee first and was allowed to repeat the testing to their satisfaction during each trial. At the end of one minute from the start of each Lachman’s Test, the researcher asked the clinician the outcome of the test. This was documented as either positive or negative. Then the clinician was asked to grade and describe the end feel. Once this trial was completed, the patients were randomly assigned again and the process
repeated for a second trial within 30 minutes of the first. Some of the key outcomes are outlined in Table 2.2.

<table>
<thead>
<tr>
<th>Test</th>
<th>Kappa coefficient</th>
<th>Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive or Negative Lachman’s Test for all examiners</td>
<td>0.51</td>
<td>76%</td>
</tr>
<tr>
<td>Inter-tester Agreement for all examiners – Trial 1</td>
<td>0.19</td>
<td>60%</td>
</tr>
<tr>
<td>Inter-tester Agreement for all examiners – Trial 2</td>
<td>0.42</td>
<td>71%</td>
</tr>
<tr>
<td>Intra-tester agreement of End Feel for all examiners</td>
<td>0.33</td>
<td>55%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weighted Kappa coefficient</th>
<th>Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intra-tester Agreement for tibial translation for all examiners</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Table 2.2 Intra-tester and inter-tester reliability of the Lachman’s Test for anterior-posterior knee joint laxity (Cooperman et al. 1990).

The amount of ACL injured patients who were judged as having a stable knee (negative Lachman’s Test) for all examiners was 29% and 23% for Trial 1 and Trial 2, respectively. Conversely, the amount of non-ACL injured patients who were judged as having an unstable knee (positive Lachman’s Test) was 54% and 43% for Trial 1 and Trial 2, respectively.

The sensitivity for all examiners in Trials 1 and 2, respectively, were 71% and 77% and specificity 46% and 57%.

The predictive value of a positive test at Trial 1 was 47% and Trial 2, 44%; whereas the predictive value of a negative test was 70% and 82%.

These results are in agreement with the meta-analysis performed by Scholten et al (2003) and states that the clinician can be confident only in diagnosing a negative Lachman’s Test (if the test is performed twice). However, the Lachman’s test is unreliable at detecting positive and graded results. Cooperman et al. (1990) suggested that this may be due to the
variation in how clinicians performed the Lachman’s test, for example, the
degree of knee flexion, patient’ relaxation and how the patient’s knee was
stabilised to perform the test.

This highlights the need for more accurate and reliable methods of
measuring anterior tibial displacement when the knee is in an anatomically and
biomechanically vulnerable range of 15° – 30° knee flexion in research
investigating the outcome of ACL reconstructive surgery.

A study by Gleeson et al. (1996a) addressed the intra-subject variability
and reliability associated with the intra-day instrumented measurements of
anterior tibial displacement in ACL deficient and normal knees. Nineteen
participants, all of whom had a unilateral ACL rupture, volunteered and
consented to be part of this study. The participants were secured in a chair with
the tested knee fixed at 25° flexion and the foot was secured at 0.26 rad of
external rotation. Two linear inductive displacement transducers were attached
perpendicular to the patella and tibial tubercle in order to measure the relative
motion. Anterior tibial force was applied in a sagittal plane and in a
perpendicular direction by an instrumented force handle, which incorporated a
load cell. The handle was positioned behind the knee 0.02m distal to the tibial
tubercle. Following a series of gentle, but rapid drawer oscillations of the force
handle, 3 intra-session anterior draw replicates of 120N and 200N was applied.
The coefficients of variation for anterior-femoral displacement in the non-injured
knee at 120N and 200N were 8.7 (±7.1)% and 5.8% (±4.9)%, respectively. In
comparison, the coefficients of variation for the ACL deficient knee were 3.6
(±3.2)% and 2.5 (±1.8)%. There was no difference between 120N and 200N,
for the robustness of the intra-class correlation coefficient, with the non-injured
and ACL deficient knees showing coefficients of 0.98 and 0.99, respectively.
The standard error of measurement (95% confidence intervals) for the non-injured knee at 120N was 15.8% and 10.6% at 200N. The ACL injured knee showed errors of 7.5% and 7.0% at 120N and 200N, respectively.

This study showed that no systematic learning effects occurred and that all changes could be attributed to random biological change or technical errors. With respect to the coefficient of variation, a stronger anterior draw force (200N) provided greater levels of reproducibility and sensitivity. The group mean of coefficient of variation and the standard error of measurement for anterior tibial displacement ranged from 2.5% - 7.0% and indicated a limited ability to distinguish physiological change in ACL function based on single trial assessments for both intra- and inter-leg comparisons. The authors stressed the importance of using a mean score of multiple trials in order to reduce measurement error. However, the number of replicates does need to capable of being delivered practically in a clinically based setting. Also, the ability to detect subtle changes may not be as necessary following ACL reconstruction due to the larger differences in translation that are commonly seen. For example, following ACL surgery, anterior translation has been shown to vary from 11.2mm (4 months post-surgery) to 4.3mm (18 months post-surgery) (Gleeson et al. 1996a).

Other commercially-available testing devices are KT 1000, Stryker Knee Laxity Tester and the Genucom Knee Analysis system and show similar levels of sensitivity and specificity amongst themselves. A recent meta-analysis by van Eck et al. (2013) found the sensitivity and specificity ranges for all of these devices to range from 0.71 (0.55 – 0.84) – 1.00 (0.93 – 1.00) and 0.76 (0.47 – 1.00) – 0.76 (0.47 – 1.00), respectively (Table 2.3).
<table>
<thead>
<tr>
<th>Instrumented Testing Device</th>
<th>Sensitivity range</th>
<th>Specificity range</th>
</tr>
</thead>
<tbody>
<tr>
<td>KT 100 at maximum manual force</td>
<td>0.88 (0.74 – 0.96) – 1.00 (0.93 – 1.00)</td>
<td>0.87 (0.79 – 0.93) – 1.00 (0.93 – 1.00)</td>
</tr>
<tr>
<td>Stryker Knee Laxity Tester</td>
<td>0.71 (0.55 – 0.84) – 0.94 (0.79 – 0.99)</td>
<td>0.82 (0.48 – 0.98) – 0.76 (0.47 – 1.00)</td>
</tr>
<tr>
<td>Genucom Knee Analysis system</td>
<td>0.71 (0.55 – 0.84) – 0.76 (0.62 – 0.87)</td>
<td>0.76 (0.47 – 1.00) – 0.88 (0.62 – 0.87)</td>
</tr>
</tbody>
</table>

Table 2.3  Sensitivity and specificity of marketed anterior-posterior knee joint laxity measurement devices (van Eck et al. 2013).

Minimal clinically important differences (MCIDs) have been investigated for anterior tibial displacement using a priori clinical and biomechanical data by Di Stasi et al. (2012). The author’s initial pilot study examined the variance and calculated the effect size between groups for tibial position and knee angle between limbs of 10 uninjured participants. They had been tested in an unperturbed one-legged standing position using an eight camera motion analysis system. The results from this study suggested using 3mm and 3.5º for MCIDs of tibial position and knee flexion, respectively. This finding is given credence by a motion analysis study performed by Chielewski et al. (2005), investigating control of the tibia in perturbed one legged stance after complete ACL rupture. A 3mm difference in tibial position was found to discriminate between participants who could cope with an ACL-deficient knee and those who could not. Due to differences in the instrumentation and methods used in this thesis compared with these previous studies, using a MCID of 3mm might be compromised. As such, this criterion could not be endorsed unreservedly but might serve as guidance only.
2.6.3 Peak force

Muscle strength is reduced following injury and/or surgery and this can be due to arthrogenic inhibition and/or due to the limitation of activity (Hopkins and Ingersoll 2000, Rice and McNair 2010). This lack of muscle strength not only limits normal function but it also increases the susceptibility to further injury (Hopkins and Ingersoll 2000, Rice and McNair 2010). In addition, muscle strength has been shown to contribute to dynamic shock absorption (Coventry et al. 2006) at the knee joint and is attributed to the prevention of over-use type injuries such as tendonopathy (Lysens et al. 1989, Mahieu et al. 2006, Ferber et al 2009) and prevention of falls (Karlsson et al. 2002, Yau et al. 2013), by means of improved agility (Mackey and Robinovitch 2006), balance (Orr et al. 2008, Horlings et al. 2009, Kondo and Pavol 2013) and co-ordination (Baltaci and Kohl 2003, Gerhem et al. 2003). Not surprisingly, muscle strengthening is an important aspect in ACL rehabilitation, aiming to improve the dynamic stability, return the patient to full function and lessen the likelihood of future injury (Risberg et al. 2001 and 2004, Keays et al. 2003, Griffin et al. 2006, Hewitt et al. 2006, Ageberg et al. 2008, Eitzen et al. 2008, van Grinsven et al. 2010, Lobb et al. 2012, Manske et al. 2012).

Peak force is the external effect of the maximal voluntary muscle activation that a subject can muster and it is used as a measurement of muscle strength. The reliability and reproducibility of assessing peak force has been investigated by Viitasalo et al. (1980), Gleeson and Mercer (1992), Gleeson et al. (2002) and more recently Minshull et al. (2009).

Viitasalo et al. (1980), in addition to other assessments within the study, measured isometric peak force of the knee extensors at 90° of knee flexion in 29 healthy male participants on two test occasions, one week apart. With
respect to peak force measurement, the first test occasion was used to familiarise the participants, the second test day involved 9 – 10 warm-up efforts followed by 5 maximal efforts, with a 5 minute recovery time between each contraction. This was then followed by 100 maximal efforts performed as quickly as possible following auditory and visual stimuli. Participants held contractions for 2.5 seconds then relaxed as quickly as possible. The signals were random and ranged from 1.4 – 4.0 seconds. EMG electrodes placed on rectus femoris, vastus lateralis and vastus medialis muscles were used in the premotor and motor times, force-time variables and relaxation variables. The coefficient of variation for peak force was 4.1% and correlation coefficient, \( r = 0.98 \). As a result of these findings Viitasalo et al. (1980) recommends that the average of two measurements will have satisfactory reliability.

The day-to-day variability and measurement reliability of both the knee flexors and extensors was investigated by Gleeson and Mercer (1992). Ten healthy male and 8 female participants were recruited and consented to this study. Following one familiarisation session, three test sessions separated by five days were adhered to. Within a test session, the participants did a 5 min. cycle ergometry warm-up for a standardised intensity. The participants were then seated on a dynamometer chair and restrained in a fixed position and the dynamometer lever arm was strapped to the preferred leg just above the ankle. This position was standardised for each participant during the day-to-day trials. Participants performed 4 submaximal and 2 maximal efforts for both knee extension and flexion. Then a series of two randomly sequenced bouts of 4 maximal efforts (with a 5 min. recovery) were performed at 1.05 rad s\(^{-1}\) (60° s\(^{-1}\)) and 3.14 rad s\(^{-1}\) (180° s\(^{-1}\)) for both the knee extensors and flexors.
The resulting coefficients of variation and standard error are represented in Table 2.4. The single measurement reliability for peak force data is represented in Table 2.5.

<table>
<thead>
<tr>
<th>Test</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Force</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V% (SE)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.05 rad s(^{-1}) (60º s(^{-1}))</td>
<td>2.9 (1.3)</td>
<td>5.0 (3.8)</td>
</tr>
<tr>
<td>3.14 rad s(^{-1}) (180º s(^{-1}))</td>
<td>3.7 (3.2)</td>
<td>3.4 (2.8)</td>
</tr>
</tbody>
</table>

Table 2.4 Day-to-day variability of the knee extensors and flexors measurement associated with peak force (Gleeson and Mercer 1992).

<table>
<thead>
<tr>
<th>Test</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Force</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R(_i)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.05 rad s(^{-1}) (60º s(^{-1}))</td>
<td>0.964</td>
<td>0.940</td>
</tr>
<tr>
<td>Trial 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trial 2</td>
<td>0.982</td>
<td>0.969</td>
</tr>
<tr>
<td>Trial 3</td>
<td>0.988</td>
<td>0.979</td>
</tr>
<tr>
<td>Trial 4</td>
<td>0.991</td>
<td>0.984</td>
</tr>
<tr>
<td>3.14 rad s(^{-1}) (180º s(^{-1}))</td>
<td>0.960</td>
<td>0.967</td>
</tr>
<tr>
<td>Trial 1</td>
<td>0.960</td>
<td>0.967</td>
</tr>
<tr>
<td>Trial 2</td>
<td>0.980</td>
<td>0.987</td>
</tr>
<tr>
<td>Trial 3</td>
<td>0.986</td>
<td>0.989</td>
</tr>
<tr>
<td>Trial 4</td>
<td>0.990</td>
<td>0.992</td>
</tr>
</tbody>
</table>

Table 2.5 Day-to-day reliability of knee the knee extensors and flexors measurement associated with peak force (Gleeson and Mercer 1992).

The authors found no systematic learning occurred and attributed changes to random variability in performance and due to technical or biological errors. Increased variability was found in the knee flexors across both sexes and the authors proposed that this might be due to the interaction of motor-neuron recruitment, rate coding, temporal patterning and co-contraction phenomena. The authors also reported that intra-class correlation coefficients and the variability of the knee extensors compares favourably with Viitasalo et al. (1980).
Similar reliability and variability data for isometric knee extensor peak force was found in eleven participants (6 male, 5 female) who were in end-stage renal failure (Gleeson et al. 2002). Following a familiarisation procedure, each participant completed three assessment sessions at the same time of day and at approximately 1 hour prior to the start of dialysis. A standardised warm-up consisted of a 3 min. cycle ride on an ergonometer. The participant was positioned in a standardised seat with the preferred knee secured at 45° flexion. Three sets of efforts were separated by 60 seconds recovery. Self-perceived extensor forces of 50%, 75% and 90% maximum effort were performed as a warm-up. This was followed by three maximal efforts this time with a 120 second recovery period between each effort. The group mean coefficient of variation score for knee extensor peak force associated with the 3 day-to-day tests was 6.6 ± 3.0%. The intra-class correlation coefficient and corresponding standard error of single measurement (95% confidence levels) for knee extensor peak force was 0.99 and 9.5%, respectively. Once again, no systematic learning effects were found across the 3 day-to-day trials. The authors stated that the assessment of the number of inter-day trials to achieve stable baseline measures can be made on reproducibility and reliability criteria alone. As in the previous studies discussed, the reliability exceeds the 0.80 threshold of clinical acceptability (Currier 1984). However, the authors suggest that depending on the outcome measure, more than 5 - 25 replicates would be required to properly discriminate between scores of different individuals with an arbitrary ±5% level of precision.

An investigative study examining single measurement reliability and reproducibility across a range of neuromuscular indices, by Minshull et al. (2009), included isometric peak force of the knee flexors at 25° knee flexion.
Twelve healthy participants (5 male, 7 female) were tested on 3 assessment sessions on 3 separate days. Following a warm-up of 2 x 50%, 75% and 100% self-perceived knee flexion efforts, the participant on receipt of a randomly given auditory signal exerted a rapid maximal effort which was held for 2-3 seconds before rapid relaxation. A 10 second recovery was allocated before this procedure was repeated. The results from this study demonstrated that the intra-session group mean coefficient of variation as 3.5 ±1.9% and a much higher inter-day group mean coefficient of variation 8.5 ±3.3%. These results suggest that while 2 trials of peak force within the same test session is sufficient in discriminating an individual's performance change of ±5% (95% confidence level), 15 trials would be required for the same level of precision for inter-day performance comparisons. Intra-class correlation coefficients and the standard errors of measurement for intra-session and inter-day group mean were 0.98 ± 0.01 (4.0 ±0.6%) and 0.93 ±0.02 (7.8 ±1.2%), respectively, and are comparable with other studies described in this review.

In summary, strength measurements for both the knee extensors and flexors are required in order to establish full function following ACL reconstruction surgery. In addition, to showing the amount of improvement over time and the possible influence of an intervention, it will also provide outcomes for measuring limb parity. Eighty percent parity of muscle strength has been suggested as return to sport criteria following ACL reconstruction surgery (Eitzen et al. 2008).

Furthermore, the restriction caused by arthrogenic inhibition and the protective phase of the post-operative rehabilitation (limiting open kinetic chain knee extension for approximately 3 months), is very likely to cause deconditioning of the quadriceps. If an autologous ipsilateral patella tendon
graft is used, it will compound the level of quadriceps’ deconditioning. As discussed in section 2.1.1, the phenomenon called the ‘ACL reflex’ may also contribute to the loss in quadriceps strength following ACL surgery (Duthon et al. 2006). Most ACL rehabilitation guides allow return to full unrestricted sporting activity from 6 months post-surgery based on the healing of the ACL graft (van Grinsven et al. 2010, Manske et al. 2012, Lobb et al. 2012). Therefore, this potentially only allows a 3 month window in which to establish adequate quadriceps muscle strength. Measurement and pattern of knee extension peak force during this rehabilitation process, will inform the clinician when an adequate amount of strength is established in order to safely progress function.

The knee flexors are considered to offer fundamental protection for the knee joint from injury. However, these too decondition as a result of the surgical insult. This is possibly due to the ACL reflex and likely if autologous ipsilateral semitendinosus and gracilis tendons have been harvested as the graft tissue (Duthon et al. 2006, van Grinsven et al. 2010 Manske et al. 2012, Lobb et al. 2012). However, unlike the quadriceps, hamstring strengthening exercises can be commenced as soon as the patient is comfortable to do so. From personal experience (>20 years) in rehabilitating post-surgical hamstring graft ACL patients, resisted knee flexion exercises are often commenced from 6 weeks post-operatively. Measurement and pattern of knee flexion peak force as with knee extension, will provide objective evidence of strength and limb-parity.

However, when interpreting the result for knee flexor peak force, it would be advisable to be mindful of the literature reviewed in this chapter that demonstrated inferior measurement reproducibility for knee flexors (Gleeson
and Mercer 1992, Gleeson et al. 2002). In addition, when exploring changes in performance abilities associated with both intra-session (for example in comparisons of the performance capabilities of ipsilateral and contralateral limbs) and inter-day assessments (for example, in the examination of extent and rate of change of performance capability over time), there is higher inter-day group variation. The variability of intra-session estimates of neuromuscular performance are frequently less than that associated with inter-day comparisons (Gleeson and Mercer 1992, Minshull et al. 2007) and as such, calculation of reliability based principally on intra-session measures may overestimate the available precision of measurement, and fail to account fully for the biological variability inherent in between-day neuromuscular performance assessments (Gleeson et al, 2002). Nevertheless, intra-session contra-lateral limb comparisons form a routine comparison in contemporary clinical practice. It might be prudent to suggest that protocols for specified levels of measurement precision be designed to accommodate the inflated variability of peak force the in post-operative knee rather than that of the contralateral control knee.

The reported results of the coefficients of variation in the literature reviewed, suggests that in applications where small differences in strength might be expected a mean score associated with at least 3 intra-day or intra-session assessments of strength would be required. This mean score will provide the basis for estimating patients’ current state in order to reduce measurement error, enhance precision and offer suitable confidence in the interpretation of data. This estimate utilises the central limit theorem, in which the estimated error of the mean score of multiple trials would be expected to vary inversely with the square root of the number of intra-individual replicates,
assuming a normal distribution (Thomas and Nelson, 1996). This will enable
the confident discrimination of intra-individual performance between the injured
and the non-injured limb, for example.

Unfortunately, no studies have yet offered calibrated MCID scores for
indices of strength performance in ACL-injured populations, probably due to the
nature of the correlational evidence linking strength to ACL-injury.

2.6.4 Rate of force development

The rate of force development (RFD) has been described as the rapidity
with which physiologically meaningful levels of force can be generated (Minshull
et al. 2009). This facet of neuromuscular function is associated with a proposed
model of knee joint stability (Section 2.3) and it has been found to correlate with
dynamic functional performance (Zebis et al. 2011).

The previously discussed studies by Gleeson et al. (2002) and Minshull
et al. (2009), investigating peak force (Section 2.6.3), also examined rate of
force development. Though Gleeson et al. (2002) and Minshull et al. (2009)
used different populations and muscle groups in their studies, the methodology
of data capture were similar. Both authors calculated the average rate of force
increase associated with the force time response between 25% and 75% peak
force of each of the three intra-session scores. Gleeson et al. (2002) calculated
the group mean coefficient of variation for the knee extensors associated with
RFD and 3 day-to-day test occasions to be 20.3 ±12.1%; the intra-class
correlation coefficients and standard error of single measurement (95%
confidence levels) 0.91 and 42.2%, respectively. In comparison, Minshull et al.
(2009) calculated the group mean coefficient of variation for the knee flexors
associated with RFD and intra-sessions test occasions to be 20.6 ±7.0%; the
intra-class correlation coefficients and standard error of single measurement (95% confidence levels) 0.81 ±0.09 and 24.5 ±5.6%, respectively. In addition, Minshull et al. (2009) calculated the group mean coefficient of variation for the knee flexors associated with RFD and inter-day test occasions to be 20.7 ±9.2%; the intra-class correlation coefficients and standard error of single measurement (95% confidence levels) 0.71 ±0.14 and 29.8 ±6.3%, respectively. Both studies demonstrate RFD has a very limited capability to discriminate subtle changes in performance and more-so in the knee flexors during intra-individual comparisons. Only RFD associated with knee extensors exceeded the clinically acceptable reliability coefficient threshold of greater than 0.8 (Currier 1984). However, when considering the standard error of single measurement, there is a limited capacity to discriminate any physiological change based on a single trial assessment with intra-group comparisons. Therefore, to improve precision and reduce measurement error, both authors suggest calculating the mean of multiple trials using the central limit theorem. A mean score of >25 trials would be required to achieve an arbitrary acceptable level of error ±5% (95% confidence limits) (Gleeson et al. 2002, Minshull et al 2009). However, this number of trials in one session when dealing with a clinical population, would not be practically acceptable. Therefore, this outcome has limited measurement utility and cannot be used in isolation to estimate true performance.

2.6.5 Electromechanical delay

Electromechanical delay (EMD) is the time lag between the onset of electrical activity and the onset of tension being developed in muscle (Vos et al. 1990, Winter and Brooks 1991, Zhou et al 1995, 1996, Minshull et al. 2007,
With respect to the dynamic stability of the knee (discussed in Section 2.3), longer EMD times have been attributed to a higher incidence of ACL injuries in females (Blackburn et al. 2009). It may also contribute with other neuromuscular factors in establishing normal function and possibly lessen this risk of future injury (Ristanis et al. 2009). Therefore, assessment of EMD following ACL reconstructive surgery and subsequent rehabilitation is an important outcome.

Over the years, a wide range of absolute EMD values have been reported in the literature for the same muscle (38.0 ms to 106.0 ms for the rectus femoris [Vos et al. 1990, Zhou et al. 1995, Zhou et al. 1996]). This has been interpreted by some researchers to represent an inherent variability of this index (Bochdansky et al. 2000). Viitasalo et al. (1980) and Minshull et al. (2009) are the only authors recently to measure single measurement reliability and reproducibility of EMD associated with knee flexors and extensors. The results from both studies are comparable. Viitasalo et al. (1980) showed the coefficient of variation to be 8.2% and an intra-class correlation coefficient of 0.93. Minshull et al. (2009) demonstrated intra-session and inter-day group mean coefficient of variation, intra-class correlation coefficient and standard error of measurement (95% confidence level) as 10.1 ±3.4%, 0.80 ±0.06 and 10.8 ±1.8%; 14.5 ±5.5%, 0.64 ±0.09 and 15.9 ±3.1%, respectively. Similar to RFD, EMD has limited capability to detect any physiological change based on a single trial assessment. Using the central limit theorem, Minshull at al. (2009) suggested that more than 15 trials would be required to achieve a discretionary acceptable level of error ±5% (95% confidence limits). Therefore, as with the measurement of RFD, same caution must be used when measuring EMD.
2.6.6 Sensorimotor performance

From personal clinical experience, excellent mechanical stability (reduced knee joint laxity) following ACL surgery does not guarantee good knee function. It is the complex interplay of neuromuscular factors, including sensorimotor performance, which assists dynamic joint stability and control (Roberts et al. 2000). Sensorimotor performance is often termed ‘proprioception’ and deficits in this performance capability following ACL injury has been associated to episodes of the knee ‘giving way’ and subsequent injuries (Ageberg et al. 2007, Gokeler et al. 2014). It is also claimed that such deficits contribute to diminished activity levels, balance and quadriceps strength (Saxton et al. 1995, Roberts et al. 2000, Angoules et al. 2011, Gokeler et al. 2014). Historically, sensorimotor training plays an important role in post-operative ACL rehabilitation (Caraffa et al. 1996). However, there is no consensus of how to best measure sensorimotor performance and a variety of measures have been used in previous studies. For example, joint-position sense, sensation of passive movement, joint angle reproduction, force reproduction and postural sway (Saxton et al. 1995, Beynnon et al. 2002, Roberts et al. 2007, Ageberg et al. 2007). The sensorimotor system is complex and relies on both spinal and cortical projections, together with reflective pathways, and as such, it is very difficult to assess (Saxton et al. 1995, Roberts et al. 2000, 2007, Beynnon et al. 2002, Ageberg et al 2007, Angoules et al. 2011).

A test-retest reliability study by Ageberg et al. (2007) for the detection of passive motion, revealed that small changes in an asymptomatic individual’s performance cannot be detected. The authors suggest this type of test would be more appropriate for observing change in groups of subjects. Intra-class
correlation coefficients ranged from 0.16 to 0.70 (95% confidence level). The starting position of 20° knee flexion had higher ICC values than those at 40°.

Better reliability at smaller joint angles were also found in a study by Angoules et al (2011), when measuring joint positions sense (JPS) and threshold of detection to passive movement (TDPM). Intra-class correlation coefficients for JPS and TDPM ranged from 0.95 – 0.99 and 0.78 – 0.96, respectively. The coefficient of variation and the standard error of measurement for JPS and TDPM ranged from 8.6% – 13.8% (0.24° – 0.35°) and 14.9% – 22.7% (0.15° – 0.25°) respectively. Minimal detectable change ranged from 0.24° to 0.41°. The authors found a statistically significant difference in both JPS and TDPM, between ACL pre-surgery and up to 3 months post-surgery compared to the contra-lateral limb. This study concludes that knee proprioception returns to normal at 6 months post ACL reconstructive surgery (regardless of the chosen autologous graft) and this situation does not change at 12 months post-surgery.

A previous study by Kraemer et al. (1997), assessed asymptomatic individuals and participants with patello-femoral pain syndrome and their ability to reproduce joint angles at the knee in sitting and standing. In sitting, the intra-class correlation coefficients and standard error of measurement ranged from 0.18 – 0.79 (1.0% – 2.4%), respectively. In standing, the intra-class correlation coefficients and standard error of measurement for joint angle replication ranged from 0.17 – 0.61 (2.1% – 3.3%), respectively. The authors found no significant statistical differences between the asymptomatic and symptomatic patients.

Of the research studies reviewed for this thesis, low to moderate reliability is found when testing sensorimotor performance using various
methods and participants. In addition, the use of passive tests to measure sensorimotor performance has been challenged, as during normal function the sensorimotor system gathers information from an active neuromuscular system (Kraemer et al. 1997, Gokeler et al. 2012). Furthermore, the constraints of funding and test availability need to be considered, when deciding an appropriate sensorimotor assessment.

2.7 Summary

The anterior cruciate ligament (ACL) is important in knee joint stability, along with the interplay of other neuromuscular and psychological factors (sections 2.2.2 – 2.3). Injury to the ACL can lead to poor function and increases the likelihood of further injury (sections 2.2 – 2.3). Rehabilitation following ACL reconstruction surgery requires a minimum of 6 months specific training, which has cost implications to the individual, society and the NHS (section 2.4). The efficacy of rehabilitation has been established using both subjectively- and objectively-measured outcomes (Section 2.4.2). Though current programmes have been reported as providing improvements in these outcomes, it might be possible to produce greater gains in functional, musculoskeletal and neuromuscular capabilities by altering the sequencing of the rehabilitative cardio-vascular and strengthening exercises. The following systematic literature review suggests why this might be the case.
2.8 Concurrent versus non-concurrent training

2.8.1 Introduction

Concurrent conditioning involves an individual training for strength and cardio-vascular endurance outcomes in close proximity i.e. within the same workout session (Dudley and Fleck 1987, Sale et al. 1990, Wilson et al. 2012). This type of training has been widely used in contemporary rehabilitative clinical practice. Positive adaptations occur as a result of cardio-vascular endurance and strength training. The adaptations to training are measured in various ways. During this review, two principal methods are used in the research literature to measure aerobic capacity and associated performance. The measures used were maximal volume of oxygen consumption ($\text{VO}_{2\text{max}}$) during an exercise intensity at which actual oxygen intake reaches a maximum beyond which no increase in effort can raise it (Hickson 1980, Dudley and Djamil 1985, Hunter 1987, Sale et al. 1990, Nelson et al. 1990, Bell et al. 1991, Hennessy and Watson 1994, Kraemer et al. 1995, Bell et al. 2000, Gravelle et al. 2000, Balabinis 2003, Häkkinen et al. 2003, Santtila et al. 2011). Alternatively, this capability has been recorded as the highest value of oxygen consumption attained on the particular test ($\text{VO}_{2\text{peak}}$). This is most commonly assessed during an incremental or other high-intensity test, designed to bring the subject to the limit of tolerance (McCarthy et al. 1995, Leveritt et al. 2003, Glowacki et al. 2004, Cadore et al. 2010, Karavirta et al. 2011). Measurement of strength was calculated (in the majority of the studies reviewed) as the maximum load that an individuals' muscle or muscle group could lift once, known commonly as one repetition maximum (1RM) (Hickson 1980, Hunter 1987, Sale et al. 1990, Volpe et al. 1993, Hennessy 1994, Kraemer 1995, Balabinis 2003, Häkkinen et
al. 2003, Karavirta et al. 2011, Cadore et al. 2010). Or, by the maximal isometric peak torque achieved, where the muscle fires but there is no movement at a joint, and this can be measured at varying joint angles (Dudley et al. 1985, Bell et al. 1991, McCarthy et al. 1995, Bell et al. 2000, Gravelle et al. 2000, McCarthy 2002, Leveritt et al. 2003, Glowacki et al. 2004, Santtila 2011). Three authors measured strength isokinetically, where the muscle contracts and shortens at a constant velocity (Nelson et al. 1990, McCarthy et al. 1995, Leveritt et al. 2003). In order to measure muscle strength isokinetically, it usually requires special, expensive training equipment that increases the load as it senses that the muscle contraction is speeding up. One author measured the maximum number of resisted repetitions that could be performed in a set time (Kraemer 2004). In addition, two studies reported the rate of force development, this is determined as the slope in the force time curve and provides an estimate of explosive strength (Häkkinen et al. 2003, Santtila 2011).

In a concurrent training format, the body must adapt to both cardio-vascular and muscle resistance training stimuli simultaneously. However, the physiological adaptations associated with each type of training are diverse and could be considered mutually exclusive (Gravelle et al. 2000, Wilson et al. 2012). It is biologically plausible that there would be competition for the body’s resources, giving rise to an interference effect (Docherty and Sporer 2000, Wilson et al. 2012).

For over three decades, the compatibility of resistance strength training and cardio-vascular endurance training has been questioned. Early articles dating back to the 1980’s, suggested that there was an interference effect brought about by training strength and endurance concurrently, resulting in the reduction in strength gains as opposed to aerobic capacity or performance

A recent meta-analysis by Wilson et al. (2012) concluded that cardio-vascular endurance training does give an interference effect when training occurs concurrently alongside resistance exercises for strength, limiting strength gains, but showing no negative effect on cardio-vascular improvement. The analysis also provided some other interesting discoveries. The inference effect might be body-part specific as concurrent training appeared to only compromise strength gains in the lower limbs not the upper limbs. The study established strength at high velocities (i.e. power) and the rate of force development are more susceptible to the inference effect. From this analysis,
and when running was separated from cycling with respect to the cardio-vascular training, it found running was significantly more detrimental to strength gains. The authors suggested that this may be due to the biomechanics of cycling closely resembling those of the exercises performed in resistance training. Interestingly, the training volume accounted for only a small portion of the inference effect.

From the literature reviewed there is a potential of strength attenuation resulting from concurrent strength and cardio-vascular training. All of the studies reviewed investigated healthy populations. No study to date has investigated the effects of these two types of training methods (concurrent; non-concurrent) in populations rehabilitating from injury or musculo-skeletal surgery.

Rehabilitative conditioning requires adaptations in muscle strength, power and cardio-vascular endurance (Häkkinen 2003); therefore, it is necessary to know whether the sequencing of rehabilitative exercise would influence outcome(s). Both maximal strength and rate of force development (RFD) are important performance characteristics that contribute to activities of daily living and might help in the prevention of falls/ trips. In addition, the role of RFD is increasingly important for various athletic purposes (Häkkinen et al. 2003). Therefore, identification of a method of training that could bring about quicker improvements in strength whilst still enabling restoration of cardio-vascular endurance capacity might have a significant and beneficial cost implication to the NHS.

This systematic review aims to investigate the effect of concurrent training and to specifically focus on limitations to the capability to make gains in strength. It includes a methodology, a search strategy and results, which are discussed in detail.
2.8.2 Method

The primary focus of the literature review was to compare the effects of combined strength and cardio-vascular endurance training (concurrent) with training for strength and endurance in isolation (non-concurrent) on musculoskeletal and neuromuscular outcome measures. Only randomised controlled studies were eligible for inclusion within the literature review. However, previously performed meta-analyses and reviews on this subject were read to establish the current and historical views regarding this topic (American College of Sports Medicine Faculty 1990, Dudley and Fleck 1987, Tan 1999, Docherty and Sporer 2000, Laursen et al. 2005, Reilley et al. 2009, Wilson et al. 2012).

Populations suffering with systemic diseases such as rheumatoid arthritis, kidney failure, and heart or lung disease were not included as these participants are likely to possess different baseline performance capabilities, and might exhibit differential performance adaptations and that are not representative of the participants tested in this thesis. Outcome measures for musculoskeletal and/ or neuromuscular performance were reported. Studies which only gave chemical and/ or cellular outcomes to training interventions would not be comparable with this study’s outcome measures and were discarded on that basis. No limitations to publication dates were given, but only full text publications in English were included.
2.8.3 Summary of criterion

*Inclusion criteria:*

Population: Male and or female over the age of 16 years.

Comparison/ Intervention: Outcomes following combined strength and endurance training or rehabilitation versus strength and/or endurance training/rehabilitation.

Results: Functional and/or neuromuscular/musculoskeletal outcomes.

Study design: Randomised controlled trial.

Time period: No date limit to Current (November 2012).

Language: The article had to be written in English.

*Exclusion criteria:*

Population: Any studies which included subjects suffering from any systemic disease, (e.g. rheumatoid arthritis, chronic obstructive airway disease or heat disease, etc.) or animal studies.

Results: Only included chemical and/or cellular responses/outcomes.

Study design: Reviews, case studies and meta-analyses were not included in the primary search, but were read to provide the ‘overall’ and general perceptions of concurrent versus non-concurrent training.

2.8.4 Search strategy

Computer searches utilising EBCOS, OVID and Athens via University of Exeter and NHS Evidence via RJAH Orthopaedic and District NHS Foundation Trust for published articles that included combined strength and endurance training with strength and/or endurance in isolation were performed. The search terms used in all of the data bases were “strength and endurance rehabilitation”, “strength and endurance training”, “strength and endurance
conditioning”, “concurrent training” “concurrent conditioning”, “Non-concurrent training” and “Non-concurrent conditioning” within the title or abstract of the electronic article.

Exclusion of studies with irrelevant content was carried out in three steps. First the title was read. If it was deemed applicable or unsure it reached the second stage and the abstract was read. Finally full manuscripts were retrieved for all the papers considered relevant. The reference list of each article was also read for any additional articles. This procedure resulted in a further ten research articles for inclusion in the review that had not been discovered by the original literature search methods.
Figure 2.5  Summary of the study selection process relating to the literature associated with concurrent versus non-concurrent conditioning/ training.
2.8.5 Coding, calculation and analysis of effect size

Each study was coded by the assessor for descriptive information including gender, age, previous training and the method, volume, sequencing and intensity of the training/testing intervention and the outcome measure(s) used. For a complete version of the coding of all the studies reviewed, including performance indicators and detailed training methods refer to Appendix D. However a brief summary of the studies is outlined in Tables 2.6 and 2.7.
Table 2.6  Overview of the literature including study participants, duration, volume and intensity of exercise, the sequencing of the strength and endurance exercises and the approximate percentage strength gains in studies where attenuation of strength gain was reported.

<table>
<thead>
<tr>
<th>Author</th>
<th>N =</th>
<th>Age (years)</th>
<th>Gender</th>
<th>Trained immediately prior to study</th>
<th>Duration of study (weeks)</th>
<th>Volume (days per week)</th>
<th>Intensity over study duration</th>
<th>Sequencing of S &amp; E</th>
<th>Strength improvement (low limb) Pre – post %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadore et al. (2010)</td>
<td>23</td>
<td>65 ±4</td>
<td>Male</td>
<td>No</td>
<td>12</td>
<td>S: 3</td>
<td>S: 6 – 20 RM 2 sets</td>
<td>Same day</td>
<td>S: 68%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E: 3</td>
<td>E: 80% - 100% HRVT 20 – 30min Cycle</td>
<td>S preceded E</td>
<td>E: 25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SE: 3, double volume</td>
<td></td>
<td>SE: 41%</td>
<td></td>
</tr>
<tr>
<td>Santtila et al. (2009)</td>
<td>72</td>
<td>19.2 ±0.9</td>
<td>Male</td>
<td>Yes</td>
<td>8</td>
<td>Basic (military) Training: ?d (=12h) BT</td>
<td>Intensity not documented</td>
<td>Same day</td>
<td>RFD [explosive strength]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Basic Training + S: 3 (=44h) BT+S</td>
<td>BT+S: 0% – 70% 1RM 1 – 40 reps 2 – 7 sets</td>
<td>Order not documented</td>
<td>BT: 2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Basic Training + E: 3 (=51h) BT+E</td>
<td>BT+E: Mainly at aerobic level 60 – 90min Various</td>
<td></td>
<td>BTS: 8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Control – no training</td>
<td></td>
<td></td>
<td>BTE: -1%</td>
</tr>
<tr>
<td>Bell et al. (2000)</td>
<td>45</td>
<td>22.3 ±3.3</td>
<td>Mix</td>
<td>No</td>
<td>12</td>
<td>S: 3</td>
<td>S: 72% – 84% 1RM 4 – 12 reps 2 – 6 sets</td>
<td>Same day</td>
<td>S: 44%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E: 3</td>
<td>E: Intervals 90% V02max 4 – 7 sets of 3min bouts, 3 min rest Cycle</td>
<td>S and E order alternated</td>
<td>E: 20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SE: 6, double volume</td>
<td></td>
<td></td>
<td>SE: 27%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Control – no training</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Häkkinen et al. (2003)</td>
<td>32</td>
<td>37 ±5 – 38 ±5</td>
<td>Male</td>
<td>No</td>
<td>22</td>
<td>S: 2</td>
<td>S: 50% – 80% 1RM 3 – 12 reps 3 – 5 sets</td>
<td>Separate days</td>
<td>S: 20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SE: 4</td>
<td>SE: S+ mix above and below aerobic threshold 30 – 90min Cycle</td>
<td></td>
<td>SE: 17%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>RFD [explosive strength] S: 86% SE: -5%</td>
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<tr>
<td>Study</td>
<td>Participants</td>
<td>Age (Mean ± SD)</td>
<td>Gender</td>
<td>Sample Size</td>
<td>Study Design</td>
<td>Training Schedule</td>
<td>Experimental Protocol</td>
<td>Control Protocol</td>
<td>Outcome Measures</td>
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<tr>
<td>Hennessy et al. (1994)</td>
<td>Male</td>
<td>23.4 ±3.6 – 24.3 ±3.6</td>
<td>56</td>
<td>8</td>
<td>Separate days</td>
<td>S: 3 E: 4 SE: 5, increased volume Control – no training</td>
<td>S: 65% - 100% RM 1 – 25 reps 3 – 6 sets E: 70% - 80% HR$_{max}$ 20 – 60mins Running</td>
<td>Separate days</td>
<td>S: 18% E: 0% SE: 13%</td>
</tr>
<tr>
<td>Nelson et al. (1990)</td>
<td>Male</td>
<td>26.0 ±1.3 – 30.0 ±2.4</td>
<td>14</td>
<td>20</td>
<td>Same day</td>
<td>S: 4 E: 4 SE: 4, double volume</td>
<td>S: 6 RM 6 reps 3 sets E: 75% - 85% HR$_{max}$ 30 – 60min Cycle</td>
<td>Same day</td>
<td>S: 22% E: 12% SE: 19%</td>
</tr>
<tr>
<td>Sale et al. (1990)</td>
<td>Male</td>
<td>21.3 ±0.8 – 21.6 ±0.5</td>
<td>16</td>
<td>20</td>
<td>Same day SE-NCON: 4 separate day</td>
<td>S: 50% - 90% 1RM 15 – 20 reps 3 – 8 sets E: 60% - 100% VO$_{2\max}$ 2 – 8 x 3min bouts, 3 min rest Cycle</td>
<td>SE-NCON: 2 same day SE-NCON: 4 separate day</td>
<td>SE-NCON: 22% SE-NCON: 12% S and E order alternated</td>
<td>SE-NCON Separate day</td>
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<tr>
<td>Hunter et al. (1987)</td>
<td>Mix</td>
<td>?</td>
<td>35</td>
<td>12</td>
<td>Same day Sequencing not documented</td>
<td>S: 4 E: 4 SE: 6 Trained SE: 6</td>
<td>S: 7 – 10 RM 7 – 10 reps 3 sets E: 75% HR$_{max}$ 20 – 40min Running</td>
<td>Same day</td>
<td>S: 21% E: 4% SE: 17% Trained SE: 23%</td>
</tr>
<tr>
<td>Dudley et al. (1985)</td>
<td>22</td>
<td>20.6 ±0.5 – 25.7 ±2.4</td>
<td>Mix</td>
<td>No</td>
<td>22</td>
<td>S: 3</td>
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<td>SE: 6, double volume</td>
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<td>S: 26 – 28 reps at 4.19 rad’s⁻¹</td>
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<td>E: 5 x 5min bouts, 5min rest</td>
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<td>Intensity not documented</td>
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<td>SE: 20%</td>
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<td>Hickson (1980)</td>
<td>23</td>
<td>18 -37</td>
<td>Mix</td>
<td>No</td>
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<td>S: 5</td>
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<td>SE: 6, double volume</td>
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<td>S: 80% 1RM</td>
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<td>E: Near to VO₂max</td>
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<td>6 x 5min bouts, 2 min rest</td>
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<td>30 – 40min run as fast as possible</td>
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<td>E: 20%</td>
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<td>SE: 2%</td>
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</table>

S: Strength  E: Cardio-vascular endurance  SE: Combined strength and cardio-vascular endurance
Table 2.7  Overview of the literature including study participants, duration, volume and intensity of exercise, the sequencing of the strength and endurance exercises and the approximate percentage strength gains in studies where no attenuation of strength gain was reported.

<table>
<thead>
<tr>
<th>Author</th>
<th>N =</th>
<th>Age (years)</th>
<th>Gender</th>
<th>Trained immediately prior to study</th>
<th>Duration of study (weeks)</th>
<th>Volume (days per week)</th>
<th>Intensity over study duration</th>
<th>Sequencing of S &amp; E</th>
<th>Strength improvement (low limb) Pre – post %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karavirta et al. (2011)</td>
<td>105</td>
<td>56 ±7</td>
<td>Male</td>
<td>No</td>
<td>21</td>
<td>S: 2</td>
<td>S: 40%-60% 1RM 5 – 12 reps 2 – 4 sets E: Mix above and below aerobic threshold 30 – 90min Cycle</td>
<td>Same day Order not documented</td>
<td>S: 14%  E: 9%  SE: 20%  C: 9%</td>
</tr>
<tr>
<td>Glowacki et al. (2004)</td>
<td>45</td>
<td>22 ±2 – 25 ±5</td>
<td>Male</td>
<td>No</td>
<td>12</td>
<td>S: 2 – 3 E: 2 – 3 SE: 5 double volume</td>
<td>S: 50% - 80% 1RM 6 – 10 reps 3 sets E: 65% - 80% HRR 20 – 40min Running</td>
<td>Separate days</td>
<td>S: 41%  E: 20%  SE: 39%</td>
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<tr>
<td>Kraemer et al. (2004)</td>
<td>35</td>
<td>21.4 ±1.4 – 24.3 ±3.6</td>
<td>Male</td>
<td>Yes</td>
<td>12</td>
<td>S: 4 E: 4 SE: 4, double volume Upper-SE: 4, double volume</td>
<td>S: 5 – 25RM 2 – 5 sets E: 80% – 100% VO_{2peak} 40min Running</td>
<td>Same day E preceded S</td>
<td>?</td>
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<tr>
<td>Leveritt et al. (2003)</td>
<td>11</td>
<td>18.3 ±0.6 – 19.3 ±1.5</td>
<td>Mix</td>
<td>No</td>
<td>6</td>
<td>S: 3 E: 3 SE: 3, double volume</td>
<td>S: 4 – 10 RM 3 sets E: 40% - 100% VO_{2peak} 5x5min bouts 5min rest Cycle</td>
<td>Same day E preceded S</td>
<td>S: 33%  E: 2%  SE: 28%</td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Age (range)</td>
<td>Gender</td>
<td>Shuffle</td>
<td>Exercise Duration</td>
<td>Notes</td>
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<tr>
<td>Balabinis et al. (2003)</td>
<td>26 Male</td>
<td>'college age'</td>
<td>Yes</td>
<td>7</td>
<td>S: 4, E: 4</td>
<td>Same day E preceded S</td>
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<td>S: 40%–95% 1RM</td>
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<td>4–40 reps</td>
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<td>1–5 sets</td>
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<td>E: 70–85% HR(_\text{max})</td>
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<td>30–90sec intervals; 2,500.m–8,200.m Sprints</td>
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<tr>
<td>McCarthy et al. (2002)</td>
<td>30 Male</td>
<td>26.5 ±1.6 – 27.9 ±1.2</td>
<td>No</td>
<td>10</td>
<td>S: 3, E: 3</td>
<td>Same day Order of S and E rotated</td>
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<td>S: 5–7 RM</td>
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<td>5–7 reps</td>
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<td>E: 70% HRR</td>
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<td>50min Cycle</td>
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<tr>
<td>Gravelle and Blessing. (2000)</td>
<td>19 Female</td>
<td>?</td>
<td>Yes</td>
<td>11</td>
<td>S: 3, SE: 3</td>
<td>Same Day S preceded E E preceded S</td>
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<td>S: 2–10 RM</td>
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<td>SE &amp; ES S + 70% VO(_\text{max})</td>
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<td>25–45min Row</td>
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<td>McCarthy et al. (1995)</td>
<td>30 Male</td>
<td>26.5 ±1.6 – 27.9 ±1.2</td>
<td>No</td>
<td>10</td>
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<td>Same Day Order of S and E rotated</td>
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<td>50min Cycle</td>
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<td>Volpe et al. (1993)</td>
<td>25 Female</td>
<td>20.1 ±0.3 – 24.3 ±1.5</td>
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<td>9</td>
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<td>S: 60–75% 1RM</td>
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<td>4–12 reps</td>
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<td>SE: 75% HR(_\text{max})</td>
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<td>25 min Walk/Run</td>
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</table>
| Bell et al. (1991) | 31 | 22.9 ±1.9 – 25 ±3.6 | Male | Yes | 12 | S: 3  
SE: 3, increased volume | S: 8 – 15 reps at ≈ 1.05 rad s⁻¹  
2 sets  
(1 x wk 30min moderate intensity aerobic session)  
SE: 85% - 90% HRₘₐₓ  
≈75% VO₂ₘₐₓ  
40 – 50mins  
Rowing | Separate days | S: 10%  
SE: 8% |

S: Strength  
E: Cardio-vascular endurance  
SE: Combined strength and cardio-vascular endurance
Where possible, Cohen’s $d$ effect size was calculated using pooled standard deviations (SD) for each study ([post-test mean – pre-test mean] ÷ pooled SD). However, some studies did not provide absolute mean data, standard deviations or standard errors within the text of the article for all or some of the outcomes. Others only provided this data in a graphical format and the values were approximated from this. Some articles did not specify whether standard deviation or standard error was used, therefore an assumption was made in these instances. The $d$ values were calculated for musculoskeletal and/or neuromuscular outcomes if they were statistically significant, according to the author (Table 2.8). If the outcome was not significant the $d$ value was only calculated if it served as a comparison to the significant finding. Cardiovascular endurance outcomes were also evaluated at this stage.

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<tbody>
<tr>
<td>Effect Size range $d_e$</td>
<td>S: 3.35 – 0.65</td>
<td>S: 0.28 – 0.64</td>
<td>S: 0.07 – 1.17</td>
<td>S: 0.02 – 0.2</td>
<td>S: 0.05 – 1.30</td>
<td>S: 0.05 – 1.74</td>
<td>S: 0.21 – 0.36</td>
<td>S: 0.01 – 0.34</td>
<td>S: 0.02 – 0.84</td>
<td>S: 0.01 – 0.34</td>
<td>S: 0.06 – 0.73</td>
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<td>E: 2.39 – 0.62</td>
<td>E: 0.02 – 0.96</td>
<td>E: 0.01 – 0.99</td>
<td>E: 0.04 – 1.72</td>
<td>E: 0.03 – 1.59</td>
<td>E: 0.03 – 1.59</td>
<td>E: 0.10</td>
<td>E: 0.03 – 0.09</td>
<td>E: 0.02 – 0.69</td>
<td>E: 0.15 – 0.27</td>
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<td>SE: 2.12 – 2.39</td>
<td>SE: 0.23 – 0.45</td>
<td>SE: 0.13 – 1.69</td>
<td>SE: 0.06 – 1.03</td>
<td>SE: 0.43 – 2.2</td>
<td>SE: 0.13 – 1.69</td>
<td>SE: 0.22</td>
<td>SE: 0.09 – 0.22</td>
<td>T-SE: 0.03 – 0.33</td>
<td>SE: 0.13 – 0.69</td>
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S: Strength group.
E: Cardio-vascular endurance group.
SE: Combined strength and cardio-vascular endurance group.
Table 2.9  Effect sizes associated with concurrent (SE) versus non-concurrent (S and E) conditioning and no attenuation of strength gains.

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<td>Effect Size range ( d = )</td>
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<td>S: 0.63 – 3.18</td>
<td>S: 0.40 – 1.77</td>
<td>S: 0.41 – 2.42</td>
<td>S: 0.81 – 1.10</td>
<td>S: 0.01 – 0.26</td>
<td>S: 0.05 – 2.54</td>
<td>S: 0.69 – 0.73</td>
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<td>E: 0.36 – 0.94</td>
<td>E: 0.62 – 0.95</td>
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<td>SE: 1.00 – 1.68</td>
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<td>SE: 0.77 – 4.75</td>
<td>SE: 0.28 – 0.78</td>
<td>SE: 0.02 – 0.49</td>
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S: Strength group.  
E: Cardio-vascular endurance group.  
SE: Combined strength and cardio-vascular endurance group.

Each research paper was rated using the PEDro rating scale. This rating scale was chosen due to its reliability and wide use in presentations and programmes on evidence-based health care practice (Maher et al. 2003, Tooth et al. 2005, Blobaum 2006, Sugimoto 2012). The scale gives positive scoring for randomisation, concealed allocation, participant blinding, assessor blinding, baseline similarity, number of participants completing the full study, intention to treat, between-group statistical comparisons and point/ variability measures (Table 2.10). The maximum score achievable is ten. The highest any of the concurrent versus non-concurrent studies achieved in this review was six (Table 2.11). This was largely due to the lack of participant and or assessor blinding to the training performed and occasionally due to the variability measures.
<table>
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<th>Criterion Number</th>
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<tr>
<td>1</td>
<td>Random Allocation</td>
<td>All participants were randomly allocated into groups.</td>
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<td>2</td>
<td>Concealed Allocation</td>
<td>Allocation was concealed.</td>
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<td>3</td>
<td>Baseline Similarity</td>
<td>The groups were similar at baseline regarding the most important prognostic indicators.</td>
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<td>4</td>
<td>Blinding of Participants</td>
<td>There was blinding of all participants.</td>
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<td>5</td>
<td>Blinding of Therapist/ Coach</td>
<td>There was blinding of all therapists or coaches who administered rehabilitation/training.</td>
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<td>6</td>
<td>Blinding of Assessors</td>
<td>There was blinding of all assessors who measured at least one key outcome.</td>
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<td>7</td>
<td>Less than 15% Drop-out</td>
<td>Measurement of at least one key outcome was provided from ≥85% of all participants initially allocated to groups.</td>
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<td>8</td>
<td>Intention to Treat</td>
<td>All participants for whom outcome measures were available received the intervention or control condition as allocated. <em>OR</em> Lost to follow-up data for at least one key outcome were analysed.</td>
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<td>9</td>
<td>Between Group Statistical Comparisons</td>
<td>Results were reported for at least one key outcome.</td>
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<tr>
<td>10</td>
<td>Effect Size and Measures of Variability</td>
<td>Measures were provided for at least one key outcome.</td>
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Table 2.11  PEDro score of the literature reviewed associated with concurrent versus non-concurrent training.

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✓  Criterion was established and clearly stated in the literature.
X  Criterion was not established or was not stated in the literature.
2.8.6 Results

From the search terms 551 articles were identified and added to the previously obtained articles. Duplicates were filtered electronically, where possible, then performed manually. Two hundred and eighty seven unique results were identified. The search was then refined to ‘relevant’, ‘irrelevant’ or ‘not sure’ based on the title, then the abstract. Thirty two full script articles were scrutinised. Following this, four of these articles investigated were excluded on the basis that they only explored the effect of sequencing of concurrent training, i.e. strength prior to or following cardio-vascular endurance in the same day and did not include isolated training as a comparison (Cadore et al. 2012, Davies et al. 2008, Collins and Snow 1993, Bell et al. 1988). One study (Jensen et al. 1996) examined a team of handball players, biasing part of the seasons’ training to strength, then at a different point in the season cardio-vascular endurance. This article only scored 3/10 on the PEDro scale; therefore, it was omitted from the full review. Three of the articles only compared cardio-vascular endurance exercise in isolation with concurrent strength and cardio-vascular endurance (Mikkola et al. 2007a, 2007b and Ferrauti et al. 2010), hence, as the influence of strengthening in isolation was not studied, these articles were also excluded. Hortobágyi et al.’s (1991) study compared light and heavy resistances with a no training control and did not include cardio-vascular endurance exercise. Abernethy et al. (1993) investigated continuous low intensity aerobic training with high intensity interval aerobic training. As such, these two papers were not included in the final review. The final paper to be excluded was Cadore (2011) as only aerobic outcomes were measured. The remaining 21 compared strength in isolation with cardio-vascular endurance and strength/cardio-vascular endurance and or cardio-vascular
endurance/strength with inconsistent findings and were included in the full review.

2.8.6.1 Strength development is compromised by concurrent training


Hickson (1985) showed significant increases in strength within the first 7 weeks of a 10 weeks intervention in the non-concurrent strength group ($d = 0.73$) compared to no significant changes in the concurrent group. This study did not present any evidence as to why these two types of exercise were incompatible, however, the authors did speculate that biochemical adaptations might be the reason. The 20-week study by Sale et al. (1990) suggested impairment in the quality of either strength or cardio-vascular endurance during concurrent training or fatigue was a possible explanation for decreased strength development during this study. Nelson et al. (1990) focused on isokinetic outcomes for strength and found that a reduction in torque gain occurred as a result of concurrent training. While Dudley et al. (1985) agreed with these findings, unfortunately no standardised measure of effect could be calculated from the study. However, there were definite and significant effect size differences following an 8 weeks training intervention by Hennessey et al. (1994). This study compared the differences of non-concurrent strength or cardio-vascular endurance training with a concurrent programme.
subjects were previously trained rugby players. Following the intervention period, the isolated strength group increased strength measured by 1 RM resisted squat exercise ($d = 1.26$), compared to the concurrent group ($d = 0.57$) and a loss in strength was discovered in the isolated endurance group ($d = -0.19$). As might have been expected no significant change in the control group ($d = -0.04$). The aforementioned studies all focused on athletic populations however, and those populations who have not been habituated to conditioning, might respond differently.

Hunter et al. (1987) found that concurrent training did inhibit strength development in previously untrained subjects. Conversely, participants included in this study that had previously trained for endurance, showed that the opposite were true. Unfortunately, the standardised effect size for strength outcomes in this study was low and similar across all three groups ($d = 0.01 - 0.34$). Strength was also shown to be attenuated by Kraemer et al. (1995). Unfortunately, as before, the effect size was low ($d = 0.02 - 0.2$). This study did surmise that non-concurrent strength and cardio-vascular endurance training cause adaptations in muscle fibre morphology and serum hormones which are different to those induced by concurrent training (Kraemer et al. 1995). The findings demonstrated that concurrent training was associated with attenuation of muscle fibre hypertrophy and increased levels of cortisol which enhanced the catabolic state (Kraemer et al. 1995).

More recently, Bell et al. (2000) separated the outcomes for the two genders across four groups, non-concurrent strength or cardio-vascular endurance, concurrent or no training control. The study found significant improvement in strength measured by 1 RM knee extension for both genders, however the females in the strength group improved far more ($d = 1.17$),
compared to the males ($d = 0.47$). A similar pattern of improvement was found in the endurance group showed difference female ($d = 0.5$), male ($d=0.07$) and the concurrent groups female ($d = 0.47$), male ($0.33$). The study demonstrated that training concurrently brought about a reduction in knee extensor strength and muscle hypertrophy, alongside increases in capillary to fibre ratio, yet the improvements in $VO_{2\text{max}}$ were similar. Once again, the authors could only offer possible suggestions regarding the reason why concurrent exercise incompatibility exists. The suggestions included elevated levels of cortisol increasing the catabolic state, the increased mechanical stress associated with combining exercise might have led to increased muscle damage and/or that certain types of exercise might be more capable of inducing detrimental physiological effects. The authors go on to suggest that closed kinetic chain exercise, such as a leg press, could be less responsive to strength attenuation. This was likely if this type of exercise was combined with a cardio-vascular endurance exercise that mimics the same movement pattern, cycling for example. The authors also state that these findings might be detrimental for the sporting community, the military and (post myocardial infarct) patients or patient populations that require development of strength and endurance as part of their rehabilitation. Interestingly, the authors also propose the potential reassurance that in the short term (less than 7 – 10 weeks) concurrent training might not have a detrimental impact to strength or endurance gains. So possibly, rehabilitation packages should be prescribed on the basis of expected recovery time.

Häkkinen (2003) found significant strength gains in both the non-concurrent strength group and the concurrent group, though the standardised
effect size was low \((d = 0.38\) and \(d = 0.17\) respectively). However, there was increased maximal voluntary neural activation of the trained muscles.

An intervention, adding strength or cardio-vascular endurance exercise to the basic training performed by the military, was examined by Santtila et al. (2009). The basic training was mainly aerobic or combat specific and this appeared to interfere with strength development and explosive power output, with the exception of the upper body. Neither the text nor figures in this article allowed effect size calculations for explosive power output or lower body strength. However, from a rehabilitation perspective, it is also useful to note from this study that subjects with low physical activity showed the highest improvements in their strength.

The main finding by Cadore et al. (2010) was the presence of an interference effect on lower body strength gains as a direct result of concurrent training. However, as Santtila (2009) found, this was not the case for upper body strength. Nevertheless, a direct comparison could not be made due to the differences in the training protocols and populations; Cadore et al. (2010) studied 23 men with a mean age of 65±4 years and Santtila et al. (2011) studied 72 military conscripts with a mean age of 19.2±0.9 years. Cadore et al.’s (2011) study showed robust effect sizes for lower body 1 RM in the strength group \((d = 3.35)\) compared to the endurance \((d = 0.96)\) and concurrent group \((d = 2.39)\). This study also found maximal electromyographic (EMG) activity adaptation was higher in the strength only group, suggesting that there is a neural component behind the interference phenomenon (Note: Electromyography is a technique for evaluating and recording the electrical activity produced by skeletal muscles, detecting the electrical potential
generated by muscle cells when these cells are electrically or neurologically activated).

The following section reviews studies that found no attenuation of strength gains, but which one study did show attenuation with respect to muscle hypertrophy (Karavirta et al. 2011) and Bell et al. (1991) did describe a ‘trend’ towards strength attenuation during the latter phase of a 12 weeks study.

2.8.6.2 Strength development is not compromised by concurrent training

In contrast to the evidence provided by the studies in sub-section 2.1.6.1, Bell et al. (1991) examined 31 participants, all of which had previous experience in either or both, resistance and cardio-vascular endurance training. The participants who’d consented to the 12 week study were separated into one of two groups associated with interventions comprising solely of strength training or strength training combined with cardio-vascular endurance. It was not stated by the authors if the group allocation was performed randomly. The outcome measures were knee extension total work and peak torque, VO$_{2\max}$, and cross-sectional area of the quadriceps. The results did not demonstrate any significant differences between the effects of the interventions. However, the authors did describe a trend towards a reduction in strength adaptations during concurrent training during the final three weeks of the study, alluding to the possibility of potential attenuation of strength over a longer time span.

Volpe et al. (1993) found no evidence to suggest an interference effect brought about by concurrent training. No significant changes were seen over 9 weeks of a training intervention. However, it is unclear from this study whether
interventions at different intensities and duration would interfere with strength gains in women.

McCarthy et al. (1995) found increases in strength ($d = 0.97$ in the strength group, $d = 0.82$ in the concurrent group) and peak power ($d = 0.51$ in the strength group, $d = 0.57$ in the concurrent group) to be congruent between groups that trained concurrently and non-concurrently. A study by Gravelle and Blessing (2000) concurs with these findings, but the authors state that a limitation to this investigation was the low sample size of 19 women and the associated reduced statistical power of the study.

Discussion of the findings of a study by McCarthy et al. (2002) stated there should be no credence given to the hypothesis of an interference of strength development with concurrent training that might be relating to neural activation. No significant differences in maximal isometric torque or maximal EMG amplitudes between training for strength in isolation and concurrently were evident following the 10 weeks study. The likelihood of over-training or muscle fatigue is a possible reason underpinning studies showing inconsistent or inconclusive results compared to those studies that do show an interference effect.

The investigation by Balabinis et al. (2003) examined 26 male basketball players over a short period of 7 weeks and found no significant differences in strength improvement when training for strength non-concurrently or concurrently. However, effect size calculations could not be derived from this article.

A 6 week intervention study by Leveritt et al. (2003) could provide no evidence of an attenuation or potentiation of strength, anaerobic or VO$_{2peak}$ development as a consequence of concurrent training and proposed that
concurrent training is more complex with respect to neuromuscular interplays than might have been expected.

Interestingly, Kraemer (2004) found that concurrent training significantly improved in all three functional tests used in the study, maximal number of push-ups (\(d = 1.96\)), maximal number of sit-ups (\(d = 1.59\)) and 2-mile run speed (\(d = 0.87\)), in an intervention involving 32 male soldiers.

Glowacki et al. (2004) provided evidence that both non-concurrent and concurrent strength training groups improved in maximum leg press and bench press outcomes to a similar extent (\(d = 1.63; 1.68\) and \(d = 1.05; 1.68\), respectively).

The most recent study in this review (Karavirta et al. 2011) examined the effects of combined endurance and strength training in healthy, older male populations (40 – 67 years old) and found no interference in outcomes for maximal strength, power or aerobic capacity during a training intervention of 21 weeks. However, diminished muscle hypertrophy was seen in the concurrently trained group over a prolonged period. Unfortunately, no effect size calculations could be established, as only percentage changes were referred to within the text of the article.

In summary, while this review provides no definitive answer as to whether concurrent training compromises strength improvements in particular, the weight of the results suggests that this might be the case. The following section investigates why cardio-vascular and strength training in close proximity might attenuate strength gains.
2.8.7 The interference effect theory

Various factors have been proposed to explain why an interference effect exists between concurrent aerobic and strength training, including fatigue, overtraining/overreaching, an increased catabolic state, alterations in motor unit recruitment patterns and changes in fibre type (Chromiak et al. 1990, Kraemer et al. 1995, Bell et al. 1991 and 2000, Docherty and Sporer 2000, Wilson et al. 2012).

Overtraining with respect to the volume of exercise endured, might have occurred in all except one of the studies reviewed, with some showing a possible interference effect (Hickson 1980, Dudley et al. 1985, Hunter et al. 1987, Nelson et al. 1990, Hennessy et al. 1994, Kraemer et al. 1995, Bell et al. 2000, Häkkinen et al. 2003, Santtila et al. 2009, Cadore et al. 2010 and others not Bell et al. 1991, Volpe et al. 1993, McCarthy et al. 1995, Gravelle et al. 2000, McCarthy et al. 2002, Leveritt et al. 2003, Balabinis et al. 2003, Glowacki et al. 2004, Kraemer et al. 2004, Karavirta et al. 2011). All of the studies involved experimental designs either combined the exercises from the strength and endurance programmes, in which three experimental groups were assessed, or cardio-vascular (CV) endurance was added to a strength programme and was compared to the effects of the strength programme alone (Bell et al. 1991, Volpe et al. 1993, Gravelle et al 2000, Häkkinen 2003). Sale et al. (1990) compared the functional effects of training for strength and CV endurance on the same day to strength and endurance on separate days, thus, this was the only iso-volumetric study that involved a standard dose of conditioning. One study added either an increased CV endurance element or a strength element to basic military training (Santtila et al. 2009). Therefore, the
suggestion of overtraining, with respect to an increased volume of exercise, cannot be the isolated reason for a possible interference effect.

level of hypoxia which is similar to training at altitude, and this stimulates peripheral adaptations. These adaptations include increases in myoglobin content, oxidative enzymes, muscle capilliarisation, mitochondrial volume, mitochondrial enzyme activity and oxidative capacity of type IIb fibres. With respect to resistance training, the authors state that training with loads ranging from 8 to 12 repetition maximum (RM) will promote muscle hypertrophy, and between 8 – 10 RM produces the highest amount of growth hormone associated with protein synthesis. Whereas 4 – 6 RM enhances neural adaptations, muscle unit activation, a faster firing frequency of muscle units, improved synchronisation and decreased contraction of antagonists. Therefore, if an athlete were to train strength between 8 -12 RM and CV endurance at 95 – 100% maximal aerobic power, the peripheral muscle would need to adapt physiologically and anatomically in very different ways and this might result in the attenuation of strength gains [Figure 2.6].

![Figure 2.6 Proposed interference effect continuum model](image)

The studies reviewed in this thesis (which were associated with concurrent versus non-concurrent training and attenuation of strength gains) were examined to find how the training and subsequent results conformed to
the interference effect continuum model proposed by Docherty and Sporer (2000). Tables 2.12 and 2.13 summarise the findings.

**Table 2.12  Presentation of previous studies that report attenuation of strength following concurrent training and how each study conforms to the proposed interference effect continuum model.**

<table>
<thead>
<tr>
<th>Author</th>
<th>Strength Training Intensity</th>
<th>CV Endurance Intensity</th>
<th>Complies with the proposed Interference Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadore et al. (2010)</td>
<td>6 – 20 RM</td>
<td>80% - 100% HR&lt;sub&gt;VT&lt;/sub&gt; 20 – 30min Cycle</td>
<td>Sometimes</td>
</tr>
<tr>
<td>Santtila et al. (2009)</td>
<td>5% - 100% 1RM</td>
<td>60 – 90m of Nordic walking, walking, running, cycling or ‘other’ endurance exercise at the ‘aerobic level’</td>
<td>Sometimes</td>
</tr>
<tr>
<td>Häkkinen et al. (2003)</td>
<td>50% - 80% 1RM</td>
<td>Mix of above and below aerobic threshold 30 – 90min Cycle</td>
<td>Sometimes</td>
</tr>
<tr>
<td>Bell et al. (2000)</td>
<td>72% – 84% 1RM</td>
<td>Intervals 90% VO&lt;sub&gt;2max&lt;/sub&gt; 4 – 7 sets of 3min bouts, 3 min rest Cycle</td>
<td>No</td>
</tr>
<tr>
<td>Kraemer et al. (1995)</td>
<td>5 – 25RM</td>
<td>85 -100% VO&lt;sub&gt;2max&lt;/sub&gt; 40 min Running</td>
<td>No</td>
</tr>
<tr>
<td>Hennessy et al. (1994)</td>
<td>65% - 100% RM</td>
<td>70% - 80% HR&lt;sub&gt;max&lt;/sub&gt; 20 – 60mins Running</td>
<td>No</td>
</tr>
<tr>
<td>Nelson et al. (1990)</td>
<td>6 RM</td>
<td>75% - 85% HR&lt;sub&gt;max&lt;/sub&gt; 30 – 60min Cycle</td>
<td>No</td>
</tr>
<tr>
<td>Sale et al. (1990)</td>
<td>50% - 90% 1RM</td>
<td>60% - 100% VO&lt;sub&gt;2max&lt;/sub&gt; 2 – 8 x 3min bouts, 3 min rest Cycle</td>
<td>No</td>
</tr>
<tr>
<td>Hunter et al. (1987)</td>
<td>7 – 10 RM</td>
<td>75% HR&lt;sub&gt;max&lt;/sub&gt; 20 – 40min Running</td>
<td>No</td>
</tr>
<tr>
<td>Dudley et al. (1985)</td>
<td>26 – 28 reps at 4.19 rad\text{s}^{-1} 2 sets</td>
<td>5 x 5min bouts, 5min rest Intensity not documented Cycle</td>
<td>Unknown</td>
</tr>
<tr>
<td>Hickson (1980)</td>
<td>80% 1RM</td>
<td>Near to VO&lt;sub&gt;2max&lt;/sub&gt; 6 x 5min bouts, 2 min rest Cycle 30 – 40min run as fast as possible</td>
<td>No</td>
</tr>
</tbody>
</table>
Table 2.13 Presentation of previous studies that report no attenuation of strength following concurrent training and how each study conforms to the proposed interference effect continuum model.

<table>
<thead>
<tr>
<th>Author</th>
<th>Strength Training Intensity</th>
<th>CV Endurance Intensity</th>
<th>Complies with the proposed Interference Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karavirta et al. (2011)</td>
<td>40%-60% 1RM 5 – 12 reps 2 – 4 sets</td>
<td>Mix above and below aerobic threshold 30 – 90min Cycle</td>
<td>No</td>
</tr>
<tr>
<td>Glowacki et al. (2004)</td>
<td>50% - 80% 1RM 6 – 10 reps 3 sets</td>
<td>65% - 80% HRR 20 – 40min Running</td>
<td>No</td>
</tr>
<tr>
<td>Kraemer et al. (2004)</td>
<td>5 – 25RM 2 – 5 sets</td>
<td>80% – 100% VO$_{2\text{max}}$ 40min Running</td>
<td>No</td>
</tr>
<tr>
<td>Leveritt et al. (2003)</td>
<td>4 – 10 RM 3 sets</td>
<td>40% - 100% VO$_{2\text{peak}}$ 5x5min bouts 5min rest Cycle</td>
<td>Sometimes</td>
</tr>
<tr>
<td>Balabinis et al. (2003)</td>
<td>40% – 95% 1RM 4 – 40 reps 1 – 5 sets</td>
<td>70 – 85% HR$_{\text{max}}$ 30 – 90sec intervals; 2.500.m – 8.200.m Sprints</td>
<td>No</td>
</tr>
<tr>
<td>McCarthy et al. (2002)</td>
<td>5 – 7 RM 5 – 7 reps 3 sets</td>
<td>70% HRR 50min Cycle</td>
<td>No</td>
</tr>
<tr>
<td>Gravelle et al. (2000)</td>
<td>2 – 10 RM 2 – 10 reps 2 – 4 sets</td>
<td>70% VO$_{2\text{max}}$ 25 – 45min Row</td>
<td>No</td>
</tr>
<tr>
<td>McCarthy et al. (1995)</td>
<td>5 – 7 RM 5 – 7 reps 3 sets</td>
<td>70% HRR 50min Cycle</td>
<td>No</td>
</tr>
<tr>
<td>Volpe et al. (1993)</td>
<td>60 – 75% 1RM 4 – 12 reps 2 – 4 sets</td>
<td>75% HR$_{\text{max}}$ 25 min Walk/Run</td>
<td>No</td>
</tr>
<tr>
<td>Bell et al. (1991)</td>
<td>8 – 15 reps at = 1.05 rad s$^{-1}$ 2 sets (1 x wk 30min moderate intensity aerobic session)</td>
<td>85% - 90% HR$<em>{\text{max}}$/=75% VO$</em>{2\text{max}}$ 40 – 50min Rowing</td>
<td>No</td>
</tr>
</tbody>
</table>

The studies reviewed do not fit into the proposed interference effect model, yet most still suggest an incompatibility when strength and CV endurance are trained in close proximity.
Though previous research leans towards the incompatibility of concurrent training, no authors have established the exact reason(s) why this is the case (Leveritt et al. 1999, Wilson et al 2012). However, a recent meta-analysis by Wilson et al. (2012) suggests that the interference effect might be body-part specific and the lower limbs appear to be more susceptible.

### 2.8.9 Discussion

Although the review was filtered primarily to analyse the effects of concurrent training on neuromuscular and musculoskeletal outcomes, some of these articles also considered the effect of concurrent training on aerobic performance or capacity. Predominantly, there is little evidence to suggest concurrent training interferes with improvements in aerobic endurance adaptations (Hickson, 1980, Dudley et al. 1985, Hunter 1987, Bell et al. 1988, Sale et al. 1990, Bell et al. 1991, Hennessy and Watson 1994, Kraemer at al 1995, McCarthy et al. 1995, Häkkinen et al. 2003, Santtila et al. 2009, Karavirta et al. 2011, Cadore et al. 2011). Gravelle et al. (2000), Balabinis et al. (2003) and Glowacki et al. (2004) are the only studies in this review to have reported a negative effect on aerobic performance as a result of concurrent training. Balabinis et al. 2003 reported a lack of improvement in aerobic performance in an isolated strength training group. This is not surprising as the strength group did not train aerobically during the assessment period (Balabinis et al. 2003). These three papers are not consistent with the findings of the majority of the studies on this subject.

Every investigation in the final review, with the exception of Volpe et al. (1993), had discrepancies in the volume of training completed. On average, the combined strength/ endurance group was double the volume that of isolated
strength and endurance groups. So, the reduced improvement of strength in the concurrent groups might have been due to over-training and thus the reason for incompatibility (McCarthy et al. 1995, Kraemer et al. 1995 McCarthy et al. 2002). However, this cannot be the sole reason as discrepancies in exercise volume was also offered as the reason for why the studies suggesting concurrent training did not cause attenuation of strength gains. The duration of the intervention periods ranged from as little as 6 weeks (Leveritt et al. 2003) to a maximum of 22 weeks (Häkkinen et al. 2003), the majority of which (6 of the 21 studies) were delivered over a 12 week period (Hunter et al. 1987, Bell et al. 1991, Bell et al. 2000, Kraemer et al. 2004, Glowacki et al. 2004, Cadore et al. 2010). Traditionally, accelerated rehabilitation following anterior cruciate ligament reconstruction takes a minimum of 6 months. Therapists are currently prescribing the sequencing of exercise blind and without any scientific evidence.

Each author’s definition with respect to concurrent training’s proximity of strength and endurance differed. For example, some studies compared an isolated strength group with a group that performed the same amount of resistance training, but also, had done additional cardio-vascular training on a separate day (Dudley et al. 1985, Bell et al. 1991, Bell et al. 2000, Häkkinen et al. 2003, Glowacki et al. 2004). Others varied the training, performing some of the concurrent training on the same day and also on separate days during the intervention period (Hunter 1987, Hennessy and Watson 1994). The remainder of the studies viewed concurrent training to be strength and cardio-vascular endurance on the same day. This means there was variability in recovery time across some of the studies.

When the combined training was performed on the same day, usually endurance preceded the strength training (Nelson et al. 1990, Volpe et al. 1993,
Kraemer et al. 1995, Leveritt et al. 2003, Balabinis et al. 2003, Kraemer et al. 2004). However, in the study by Cadore et al. (2010), strength preceded endurance. Dudley et al. (1985), Sale et al. (1990), Hennessy and Watson (1994), McCarthy et al. (1995), McCarthy et al. (2002) alternated the sequencing of strength and endurance each day or week of training. Three of the studies reviewed, Hickson (1980), Santtila et al. (2011) and Karavirta et al. (2011), did not document the order of the training performed in the concurrent groups. The study by Gravelle et al. (2000) included two separate concurrent groups within the study and sequenced endurance before strength and vice versa.

Further detail of the training interventions and populations used in each study included in this review is documented in Appendix D – Tabular description of the literature associated with non-concurrent versus concurrent training (including Cohen’s $d$ and PEDro score) with respect to neuromuscular outcomes.

Upon completion of this review, there was an obvious gap in the literature with no clear understanding or consensus of the best pattern or sequence of training for optimising the adaptive responses to strength or cardiovascular endurance training.

The reasons for inconsistent findings in the previous studies might be due to variations in training volume, intensity, frequency, mode, initial training status of the subjects, and the integration of the training (McCarthy et al. 1995, 2002). In addition, no study examined a population rehabilitating from injury or surgery. There is a clinical need for a randomised study designed to incorporate an assessment of the effects of the interaction of these variables on function and physical capabilities.
An investigation examining standardised training variables over a period of time typical to rehabilitation following common place surgeries (such as ACL reconstruction), assessing the musculoskeletal, neuromuscular, functional and self-perceived outcomes in post-operative patients would offer insight and be a novel area of medical research. It also has the potential to change current rehabilitative practice.

2.9 Conclusion

This review highlights that there is potential for attenuation of strength gains when training for strength and cardio-vascular endurance concurrently. No study to date has investigated the effects of concurrent versus non-concurrent training in injured populations or patients rehabilitating from injury. The findings from such a study would be clinically significant and might have serious financial implications to the NHS.

A limitation of all the previous studies associated with concurrent versus non-concurrent training (with the exception of Volpe et al. 1993) was the lack of matching of training volume, giving rise to possible negative effects of ‘overtraining’, thus blurring the cause of attenuation of strength gains [Tables 2.6 and 2.7]. Furthermore, a limitation of the study by Gravelle and Blessing (2000) was the small sample size which reduced the study’s statistical power. Therefore, it is important that future studies are balanced in the implementation of training interventions, ensure that the number of participants is sufficient to offer statistical power and feature a duration that is sufficiently lengthy to properly reflect strength improvements brought about by training.

Within the NHS, anterior cruciate ligament surgery is relatively common place and rehabilitation from surgical reconstruction takes 6 – 9 months. During
the first three months, there is a significant loss in muscle strength due to limited activity prescribed to protect the graft tissue. After this time, emphasis is placed on regaining strength, proprioception, power and agility in a progressive and clinically appropriate way. If sequencing of rehabilitative exercise affects the speed at which strength gains can be achieved, it could have the potential to change current clinical practice.

In summary, this review reveals that there is a scientific and clinical need for a randomised control trial to compare concurrent and non-concurrent rehabilitative training on self-perceived, functional, musculoskeletal and neuromuscular performance, following ACL reconstructive surgery.

Ultimately, rehabilitation aims to restore full function. With respect to ACL reconstruction, this requires dynamic knee joint stability, which potentially involves the complex interplay of musculoskeletal and neuromuscular factors. Therefore, the premise of this thesis was to assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on (a) subjective (IKDC; KOOS; PP [Chapter 4]) and objective measures of function (HOP [Chapter 5]) (primary outcome measures for this thesis), and (b) objective measures of musculoskeletal (ATFD) and neuromuscular performance (PF, EMD, RFD, SMP [Chapter 5]) (secondary outcome measures), in patients with anterior cruciate ligament deficiency. The secondary aim was to evaluate the relationships amongst a subjective outcome of function (IKDC), an objective outcome of function (HOP), and the secondary objective outcomes of musculoskeletal (ATFD) and neuromuscular (PF, RFD, EMD, SMP) performance at pre-surgery and at 24 weeks post-surgery (Chapter 6).
Chapter 3:

General Methods
Chapter 3: General Methods

3.1 Overview of the study

The purpose of this research was to evaluate the benefit of novel post-operative rehabilitation aimed specifically at improving physiological, functional and self-perceived capability following surgery for anterior cruciate ligament (ACL) injury.

3.1.1 Randomised control trial part 1 – subjectively-measured outcomes [Chapter 4]

The primary self-perceived outcome measure of function was assessed via the International Knee Documentation Committee (IKDC) subjective knee evaluation form (2000), the Knee injury and Osteoarthritis Outcome Score (KOOS) and the Performance Profile (PP). These measures were analysed to assess the difference in self-perceived function between two methods of rehabilitation following ACL reconstruction surgery, traditional concurrent (CON) and the intervention, non-concurrent (NCON) rehabilitation. These self-perceived outcome measures are analysed separately in Chapter 4 although they were completed within the same assessment session as the primary functional objective measure and secondary musculoskeletal and neuromuscular measures reported in Chapter 5.

In addition, the influence of the assessor-patient interaction and the possibility of clinical approbation affecting the self-perceived outcomes (IKDC, KOOS, PP) was examined using a third group, acting as a further control, that followed the traditional CON rehabilitation, but were only assessed pre-operatively and at 48 weeks post-operatively (Limited testing CON).
3.1.2 Randomised control trial part 2 – objectively-measured outcomes [Chapter 5]

The primary objective outcome measure of function was assessed via hop for distance (HOP) and the secondary objective measurements of musculoskeletal and neuromuscular performance were determined by the measurement of anterior tibio-femoral displacement (ATFD), peak force (PF), rate of force development (RFD), electromechanical delay (EMD) and sensorimotor performance (SMP). These indices were used to analyse the effects of rehabilitation, comparing the traditional CON ACL rehabilitation with a new method, NCON rehabilitation.

Assessment of clinical approbation on the primary and secondary objective outcomes possibly caused by the patient-assessor interaction during testing sessions was examined using a third group that followed the traditional CON rehabilitation but were only assessed pre-operatively and at 48 weeks post-operatively (Limited testing CON).

3.1.3 Relationships amongst subjectively-measured and objectively-measured outcomes [Chapter 6]

The relationships amongst subjective (self-perceived) measure of knee function (International Knee Documentation Committee [IKDC] knee evaluation form, a primary outcome measure of the thesis) and objective measures of function (single-leg hop for distance [HOP]), musculoskeletal (anterior tibio-femoral displacement [ATFD; knee laxity]), neuromuscular performance (peak force [PF, strength], rate of force development [RFD], electromechanical delay [EMD]), force-error [FE]), at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii)
amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery were examined.

3.2 Methods

3.2.1 Participant recruitment
Eighty two patients (69 males [age: 35.4 ± 8.6 yr (range 19 to 50 yr); height = 1.79 ± 0.07 m; body mass = 83.6 ± 11.4 kg; time from injury to surgery 9.4 ± 6.9 months [mean ± SD]; 13 females [age: 41.6 ± 7.6 yr (range 36 to 49 yr); height = 1.68 ± 0.09 m; body mass = 69.7 ± 10.7 kg; time from injury to surgery 6.4 ± 4.9 months]), electing to undergo unilateral ACL-reconstructive surgery (semitendinosus and gracilis graft (commonly referred to as a hamstring graft) or central third, bone-patella tendon-bone graft) at a U.K. National Health Service Foundation Trust hospital, gave their informed consent to participate in the study. Patients were treated by two consultant orthopaedic surgeons (DR; SR) of similar experience and practice (> 12 ACL reconstruction surgeries per month) using agreed and matched surgical procedures. Patients meeting inclusion criteria from a randomly-sequenced cohort awaiting surgery or subsequently presenting with injury, were offered participation.

3.2.2 Inclusion and exclusion criteria
No exclusions were made on the basis of gender or race. Only patients over 16 years-old who were deemed musculoskeletally and mentally mature were invited to take part in the study. Patients suffering with bilateral knee pathologies at the time of consent were excluded as the contra-lateral knee would not suffice as a control. Multiple ligament injuries that would require
adaptation to the standard rehabilitative practice were also excluded. No exclusions were made regarding the autologous graft choice of hamstring or patella tendon. Patients with systemic conditions such as rheumatoid arthritis, chronic obstructive airways disease or cardiac pathology were excluded on the basis that their physiological responses to training would be compromised and their physical ability to take part in the rehabilitation programmes investigated in this study would prove difficult and clinically inappropriate.

To summarise;

**Inclusion Criteria:**

Adults over 16 years of age and mentally mature
Listed for ACL reconstructive surgery following informed surgical consent
Patients were under the care of one of two surgeons identified to perform the surgery
Autologous graft tissue; either patella tendon or semitendinosus and gracilis from the ipsilateral leg
Agreed to attend RJAH Orthopaedic Hospital for post-operative rehabilitation
All ethnic groups
Male or Female
Agreed to participate in the study

**Exclusion Criteria:**

Patients with systemic pathologies
Bilateral knee injuries at the time of consent
Multiple ligament injuries to the knee
Declined to participation in the study
3.2.3 Ethical approval

This study met the ethical standards suggested by Harriss and Atkinson (2009), and the study was approved by the Ethics Committee for Human Testing of the University of Exeter, UK, and by the Shropshire area NHS Ethics Committee (REC reference 05/Q2601/36) and had received scientific merit approval from the Research Committee of Robert Jones and Agnes Hunt Orthopaedic and District Hospital Foundation NHS Trust, UK. The study can be tracked using the reference code R5613 with respect to The National Institute for Health Research (NIHR) Clinical Research Network (CRN).

3.2.4 Consent

The patients who were approached had consented for ACL autologous reconstructive surgery by one of the two surgeons involved in this study and were willing to attend specified NHS Foundation Trust for rehabilitation. The study was discussed, including the potential risks and benefits and the Patient Information Sheet was issued (see Appendix E – participation information sheet and Appendix F – thesis participation consent form). The patients were contacted approximately one week after this initial meeting and were given the opportunity to ask further questions and to participate in the study. All participants were fully aware that they could withdraw from the study without giving any reason and this would in no way alter the care they received.
3.2.5 Randomisation

Patients were prospectively randomised to one of three groups:

**CON** (n=31 [29♂, 2♀ [age: 37.5 ± 8.8 yr (range 19 to 50 yr); height = 1.77 ± 0.07 m; body mass = 81.4 ±12.3.0 kg; time from injury to surgery 9.4 ± 6.9 months]; n=9 lost to follow-up) comprising a standardised and established (>5 yr) programme of exercise rehabilitation used in current clinical practice (24 weeks of structured and supervised rehabilitation conditioning [705 ± 10 minutes]) focusing on progressive mobility, strength and endurance conditioning;

**NCON** (n=33 [27♂, 6♀ [age: 36.6 ± 9.0 yr (range 21 to 50 yr); height = 1.76 ± 0.09 m; body mass = 82.4 ± 11.1 kg; time from injury to surgery 8.3 ± 6.7 months]; n=7 lost to follow-up) comprising and matching the type, volume and intensity associated with the programme of exercise rehabilitation prescribed in CON, but modified to include the novel and specific phasing of strength and endurance exercises and designed to minimise physiological inhibition associated with concurrent strength and endurance conditioning;

**Limited testing CON** (n=18 [13♂, 5♀ [age: 34.2 ± 8.1 yr (range 23 to 50 yr); height = 1.79 ± 0.09 m; body mass = 81.1 ± 17.3 kg; time from injury to surgery 9.1 ± 7.2 months]; n=3 lost to follow-up) matching the programme of exercise rehabilitation used in CON but with purposeful minimised attention and assessor-patient interaction during rehabilitation outcome assessments other than that at the recruitment to the study (pre-surgery) and at its completion (48 weeks post-surgery). This control condition was included to quantify the influence of the test administrator during assessment procedures and potential clinical and social approbation that might have been expected to enhance outcome.
Table 3.1 summarises the anthropometric and clinically-related characteristics of each patients’ group.

<table>
<thead>
<tr>
<th>Group</th>
<th>Male (n =)</th>
<th>Female (n =)</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Body Mass (kg)</th>
<th>Time from injury to surgery (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CON</td>
<td>29</td>
<td>2</td>
<td>37.7 ± 8.8</td>
<td>1.77 ± 0.07</td>
<td>81.4 ± 12.3</td>
<td>9.4 ± 6.9</td>
</tr>
<tr>
<td>NCON</td>
<td>27</td>
<td>6</td>
<td>36.6 ± 9.0</td>
<td>1.76 ± 0.09</td>
<td>82.4 ± 11.1</td>
<td>8.3 ± 6.7</td>
</tr>
<tr>
<td>Limited testing CON</td>
<td>13</td>
<td>5</td>
<td>34.2 ± 8.1</td>
<td>1.79 ± 0.09</td>
<td>81.1 ± 17.3</td>
<td>9.1 ± 7.2</td>
</tr>
</tbody>
</table>

**Table 3.1 Summary of the anthropometric and clinically-related characteristics of each patients’ group.**

All participants had been involved in recreational to high-level sports. Fifty-one percent of patients had presented with right knee injury with 58.5% of patients reporting injury to the preferred leg. Eleven percent of patients had obtained the injury via normal activities of daily living; 65% patients had obtained the injury via a non-contact incident whilst performing sport, and 24% by means of a contact incident during sport. The mechanism of injury was categorised as either ‘contact’ or ‘non-contact’: ‘contact’ if there had been contact with another individual resulting in the injury, regardless of where on the body the contact had occurred. Seventy percent of the patients received an autologous hamstring (semitendinosus and gracilis tendons) ACL reconstruction and 30% received an autologous patella tendon graft reconstruction.
3.2.6 Batch allocation procedure

Following study consent, patients were sequentially batch-allocated using computer generated randomly-ordered sequences of 5 numbers (1, 2, 3, 4 and 5), in which numbers 1 and 3, 2 and 4, and then 5 had been previously set against patients presenting in batches of 5, being allocated sequentially to NCON, CON, and Limited testing CON groups, respectively. This sequence optimised/ focused experimental design sensitivity amongst comparisons associated with the two primary ‘arms’ of the study (NCON versus CON).

The consort diagram [Figure 3.1] summarises the recruitment and allocation pathway.
Figure 3.1 Consort Diagram – summary of the number of patients recruited, the random allocation and those lost to follow-up.
3.2.7 Intention to treat [Chapters 4 and 5]

Patients lost to follow-up did so at varying assessment sessions [Figure 3.1]. No secondary injuries occurred to any of the patients during the rehabilitation or assessment process. Therefore, secondary injury was not a contributing factor in lost to follow-up. However, as stated in the patient information (see Appendix E), patients who were lost to follow-up were not questioned as to why they chose to leave the study at a particular point, although 10 of the 19 patients did voluntarily offer the reason of work/life commitments intruding on the time available to contribute to the research study.

The potential influences of bias and compromised external validity on this study’s findings, associated with altered group composition and altered patterns of outcome data due to patients being lost to follow-up, were assessed using separate ANOVAs involving factors of group (NCON; CON; Limited CON; Lost to-follow-up) by leg (injured; non-injured) with repeated measures on the last factor. All subjective and objective outcomes were assessed at baseline. With the exception of peak force associated with the knee flexor musculature (3.2% and 2.4% lower scores for lost to follow-up, injured and non-injured legs, respectively; $F_{(3.0,.97.0)GG} = 3.9; \ p<0.05$), all other outcomes showed statistically similar performance characteristics at baseline amongst the group mean scores for patients within the experimental groupings and those patients who had been lost to-follow-up. This suggested cautiously, that the potential for biasing of findings in this study, would have intruded to a very minor extent only, if at all.
3.3 Intervention

After surgery, all patients were treated by the same physiotherapist for the duration of their rehabilitation period with partial-blinding to intervention allocation and outcome assessments. Early phases of rehabilitation in current clinical practice (CON and Limited testing CON: 0 - 6 weeks post-surgery) comprised standard rehabilitation exercises concentrating on gaining full range of motion, especially terminal extension/ hyper-extension in the injured limb [Figure 3.2], gait re-education, static cycling, the use of rowing and elliptical cross trainer machines, step-ups, active and resisted exercises of the upper body, core stability and proprioceptive activities.

During the intermediate phase (6 – 12 weeks post-surgery), proprioceptive work was increased, resisted exercises (with the exception of through-range open-kinetic-chain extension) were introduced [Figure 3.3] and the difficulty of other activities (e.g., step-ups, one-legged dips) was increased; ‘Early plyometric’ exercises were added in the form of jumps, leaps and hops in partial-weight bearing scenarios using a set of parallel bars in front of a mirror to correct any biomechanical errors and to familiarise the patient to using the lower limb joints for synchronised work at speed [Figure 3.4].
During the late phase of the rehabilitation (12 – 24 weeks post-surgery), there was an increased emphasis on dynamic neuromuscular training including plyometric and agility drills [Figures 3.5 – 3.9]. Once an appropriate level of eccentric quadriceps control was established, interval treadmill walk/ jog was added, progressing direction, volume and pace, systematically; full-weight bearing double leg jumps on the spot was progressed to travelling forwards, backwards, sideways, 180° rotations and jumping from a step, advancing to single leg work. From approximately week 16, predictable twisting/ turning
agility circuits were added under supervision, and from week 20, unpredictable sports-specific agility and perturbation training on the sports field was included.

Figure 3.5
Example of an open kinetic knee extensor exercise performed on a gym ball to engage core stability and to improve proprioception.

Figure 3.6
Example of an open kinetic exercise isolating the knee extensors.

Figure 3.7
Example of a sport specific proprioceptive exercise.
This naturally progressed to contact sport training from 24 weeks and a graduated return to all sporting activity thereafter [Refer to Appendix A - RJAH anterior cruciate ligament rehabilitation guide for greater detail].

The NCON group followed this same guide of activity progression. However, heavy resisted exercises were performed on a separate day to cardio-vascular training when the latter had been scheduled to exceed 30 minutes in duration. Over the month, each participant regardless of group performed on average, the same volume and intensity of resisted, CV, stability, proprioception, plyometric and agility training.
Examples of Early, Intermediate, Late Phase rehabilitation showing the differences in the sequencing of exercises between the groups are shown in Table 3.2, 3.3 and 3.4

Table 3.2  Example of the differences in the patterning of the delivery of rehabilitative conditioning between CON, NCON and Limited testing CON groups during a single-week associated with Early Phase rehabilitation. (Mode, intensity and volume of exercise were matched between groups over successive phases of rehabilitation and across the complete 6-month rehabilitation programme).

<table>
<thead>
<tr>
<th>Example Week</th>
<th>Early Phase</th>
<th>Groups CON and Limited testing CON</th>
<th>NCON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td></td>
<td>Vastus Medialis Oblique (VMO) exercise protocol Individualised core stability exercises</td>
<td>Vastus Medialis Oblique (VMO) exercise protocol Individualised core stability exercises</td>
</tr>
<tr>
<td>Tuesday</td>
<td></td>
<td>VMO exercise protocol Proprioception exercise e.g. one legged balance eyes open → eyes closed 20 – 30 minutes cardio-vascular CV exercise e.g. bike, row, X-trainer, stepper 2 x 5 Repetition Maximum (RM) weights 1x 20 RM 10 – 20 minutes CV</td>
<td>VMO exercise protocol Proprioception exercise e.g. one legged balance eyes open → eyes closed 10 – 20 minutes cardio-vascular CV exercise e.g. bike, row, X-trainer, stepper 3 x 5 Repetition Maximum (RM) weights 5 – 10 minutes CV</td>
</tr>
<tr>
<td>Wednesday</td>
<td></td>
<td>VMO exercise protocol Partial Weight Bearing (PWB) plyometrics e.g. double leg jumps, leaps, high knees, heel flicks.</td>
<td>VMO exercise protocol Partial Weight Bearing (PWB) plyometrics e.g. double leg jumps, leaps, high knees, heel flicks.</td>
</tr>
<tr>
<td>Thursday</td>
<td></td>
<td>VMO exercise protocol Rest</td>
<td>VMO exercise protocol Rest</td>
</tr>
<tr>
<td>Friday</td>
<td></td>
<td>VMO exercise protocol 20 – 30 minutes CV e.g. bike, row, X-trainer, stepper 1 x 5 RM 2 x 20 RM 10 – 20 minutes CV</td>
<td>VMO exercise protocol 30 minutes CV e.g. bike, row, X-trainer, stepper 3 x 20RM 10 – 20 minutes CV</td>
</tr>
<tr>
<td>Saturday</td>
<td></td>
<td>VMO exercise protocol 20 – 30 minutes CV e.g. bike, row, X-trainer, stepper 2 x 5 RM 1x 20 RM 10 – 20 minutes CV</td>
<td>VMO exercise protocol 10 – 20 minutes CV e.g. bike, row, X-trainer, stepper 3 x 5 RM 5 – 10 minutes CV</td>
</tr>
<tr>
<td>Sunday</td>
<td></td>
<td>VMO exercise protocol Rest</td>
<td>VMO exercise protocol Rest</td>
</tr>
</tbody>
</table>

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Table 3.3  Example of the differences in the patterning of the delivery of rehabilitative conditioning between CON, NCON and Limited testing CON groups during a single-week associated with Intermediate Phase rehabilitation. (Mode, intensity and volume of exercise were matched between groups over successive phases of rehabilitation and across the complete 6-month rehabilitation programme).

<table>
<thead>
<tr>
<th>Example Week 8</th>
<th>Groups CON and Limited testing CON</th>
<th>NCON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>VMO exercise protocol</td>
<td>VMO exercise protocol</td>
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<tr>
<td></td>
<td>Individualised core stability exercises</td>
<td>Individualised core stability exercises</td>
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<tr>
<td></td>
<td>30 – 45 minutes CV e.g. bike, row, X-trainer, stepper, swimming (avoiding breast-stroke leg kick)</td>
<td>10 – 20 minutes CV e.g. bike, row, X-trainer, stepper, swimming (avoiding breast-stroke leg kick)</td>
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<tr>
<td></td>
<td>2 x 5 RM</td>
<td>3 x 5 RM</td>
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<td>1 x 20 RM</td>
<td>5 – 10 minutes CV</td>
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<td></td>
<td>10 – 20 minutes CV</td>
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<tr>
<td>Tuesday</td>
<td>VMO exercise protocol</td>
<td>VMO exercise protocol</td>
</tr>
<tr>
<td></td>
<td>PWB plyometrics e.g. double leg jumps, leaps, high knees, heel flicks.</td>
<td>PWB plyometrics e.g. double leg jumps, leaps, high knees, heel flicks.</td>
</tr>
<tr>
<td></td>
<td>Proprioception exercises e.g. one legged balance with small knee bends, using theraband™, throw and catching, kicking with non-injured leg.</td>
<td>Proprioception exercises e.g. one legged balance with small knee bends, using theraband™, throw and catching, kicking with non-injured leg.</td>
</tr>
<tr>
<td>Wednesday</td>
<td>VMO exercise protocol</td>
<td>VMO exercise protocol</td>
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<tr>
<td></td>
<td>Individualised core stability exercises</td>
<td>Individualised core stability exercises</td>
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<tr>
<td>Thursday</td>
<td>VMO exercise protocol</td>
<td>VMO exercise protocol</td>
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<tr>
<td></td>
<td>30 – 45 minutes CV e.g. bike, row, X-trainer, stepper, swimming (avoiding breast-stroke leg kick)</td>
<td>45 minutes or more CV e.g. bike, row, X-trainer, stepper</td>
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<td></td>
<td>1 x 5 RM</td>
<td>3 x 20 RM</td>
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<td></td>
<td>2 x 20 RM</td>
<td>5 – 10 minutes CV</td>
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<td></td>
<td>10 – 20 minutes CV</td>
<td></td>
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<tr>
<td>Friday</td>
<td>VMO exercise protocol</td>
<td>VMO exercise protocol</td>
</tr>
<tr>
<td></td>
<td>30 – 45 minutes CV e.g. bike, row, X-trainer, stepper, swimming (avoiding breast-stroke leg kick)</td>
<td>45 minutes or more CV e.g. bike, row, X-trainer, stepper</td>
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<td>1 x 5 RM</td>
<td>3 x 20 RM</td>
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<td></td>
<td>2 x 20 RM</td>
<td>10 – 20 minutes CV</td>
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<td>10 – 20 minutes CV</td>
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<tr>
<td>Saturday</td>
<td>VMO exercise protocol</td>
<td>VMO exercise protocol</td>
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<tr>
<td></td>
<td>Individualised core stability exercises</td>
<td>Individualised core stability exercises</td>
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<td></td>
<td>30 – 45 minutes CV e.g. bike, row, X-trainer, stepper, swimming (avoiding breast-stroke leg kick)</td>
<td>10 – 20 minutes CV e.g. bike, row, X-trainer, stepper, swimming (avoiding breast-stroke leg kick)</td>
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<td>2 x 5 RM</td>
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<td>1 x 20 RM</td>
<td>5 – 10 minutes CV</td>
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<td>10 – 20 minutes CV</td>
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<tr>
<td>Sunday</td>
<td>VMO exercise protocol</td>
<td>VMO exercise protocol</td>
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<td></td>
<td>Rest</td>
<td>Rest</td>
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</tbody>
</table>
Table 3.4  Example of the differences in the patterning of the delivery of rehabilitative conditioning between CON, NCON and Limited testing CON groups during a single-week associated with Late Phase rehabilitation. (Mode, intensity and volume of exercise were matched between groups over successive phases of rehabilitation and across the complete 6-month rehabilitation programme).

<table>
<thead>
<tr>
<th>Example Week 20 Late Phase</th>
<th>Groups CON and Limited testing CON</th>
<th>NCON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Monday</strong></td>
<td>Individualised core stability exercises</td>
<td>Individualised core stability exercises</td>
</tr>
<tr>
<td></td>
<td>Proprioception exercises e.g. throwing, catching, kicking on Trampette or sit-fit™ using alternate legs, hopping on a mark for accuracy, walking, dipping jumping and hopping on a foam beam.</td>
<td>Proprioception exercises e.g. throwing, catching, kicking on Trampette or sit-fit™ using alternate legs, hopping on a mark for accuracy, walking, dipping jumping and hopping on a foam beam.</td>
</tr>
<tr>
<td><strong>Tuesday</strong></td>
<td>Individualised core stability exercises</td>
<td>Individualised core stability exercises</td>
</tr>
<tr>
<td></td>
<td>Proprioception exercises e.g. throwing, catching, kicking on Trampette or sit-fit™ using alternate legs, hopping on a mark for accuracy, walking, dipping jumping and hopping on a foam beam.</td>
<td>Proprioception exercises e.g. throwing, catching, kicking on Trampette or sit-fit™ using alternate legs, hopping on a mark for accuracy, walking, dipping jumping and hopping on a foam beam.</td>
</tr>
<tr>
<td></td>
<td>Plyometrics e.g. split-squat jumps, lateral hurdle jumps, alternate leg ‘push-offs’, cone jumps with 180º turn.</td>
<td>Plyometrics e.g. split-squat jumps, lateral hurdle jumps, alternate leg ‘push-offs’, cone jumps with 180º turn.</td>
</tr>
<tr>
<td><strong>Wednesday</strong></td>
<td>45 – 60 minutes CV e.g. bike, row, X-trainer, stepper, swimming, treadmill.</td>
<td>10 – 20 minutes CV e.g. bike, row, X-trainer, stepper, swimming, treadmill.</td>
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<tr>
<td></td>
<td>2 x 5 RM</td>
<td>3 x 5 RM</td>
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<tr>
<td></td>
<td>1 x 20 RM</td>
<td>5 – 10 minutes CV</td>
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<td></td>
<td>10 – 20 minutes CV</td>
<td></td>
</tr>
<tr>
<td><strong>Thursday</strong></td>
<td>Plyometrics e.g. split-squat jumps, lateral hurdle jumps, alternate leg ‘push-offs’, cone jumps with 180º turn.</td>
<td>Plyometrics e.g. split-squat jumps, lateral hurdle jumps, alternate leg ‘push-offs’, cone jumps with 180º turn.</td>
</tr>
<tr>
<td></td>
<td>Individualised core stability exercises</td>
<td>Individualised core stability exercises</td>
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<tr>
<td><strong>Friday</strong></td>
<td>Individualised core stability exercises</td>
<td>Individualised core stability exercises</td>
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<tr>
<td></td>
<td>45 – 60 minutes CV e.g. bike, row, X-trainer, stepper, swimming, treadmill.</td>
<td>60 minutes or more CV e.g. bike, row, X-trainer, stepper, swimming treadmill.</td>
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<td></td>
<td>1 x 5 RM</td>
<td>3 x 20RM</td>
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<tr>
<td></td>
<td>2 x 20 RM</td>
<td>10 – 20 minutes CV</td>
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<tr>
<td></td>
<td>10 – 20 minutes CV</td>
<td>Agility Drill e.g. Falling starts, 20 yard shuttles, T-Drill, Squirms.</td>
</tr>
<tr>
<td></td>
<td>Agility Drill e.g. Falling starts, 20 yard shuttles, T-Drill, Squirms.</td>
<td></td>
</tr>
<tr>
<td><strong>Saturday</strong></td>
<td>VMO exercise protocol</td>
<td>VMO exercise protocol</td>
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<tr>
<td></td>
<td>Individualised core stability exercises</td>
<td>Individualised core stability exercises</td>
</tr>
<tr>
<td><strong>Sunday</strong></td>
<td>Agility Drill e.g. Falling starts, 20 yard shuttles, T-Drill, Squirms.</td>
<td>Agility Drill e.g. Falling starts, 20 yard shuttles, T-Drill, Squirms.</td>
</tr>
<tr>
<td></td>
<td>45 – 60 minutes CV e.g. bike, row, X-trainer, stepper, swimming, treadmill.</td>
<td>10 – 20 minutes CV e.g. bike, row, X-trainer, stepper, swimming, treadmill.</td>
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<td>2 x 5 RM</td>
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<td></td>
<td>1 x 20 RM</td>
<td>5 – 10 minutes CV</td>
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<td></td>
<td>10 – 20 minutes CV</td>
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</table>
The precise dosing, volume and intensity of rehabilitation was controlled in this study by patient self-monitoring of his/her own physical rehabilitation activities by weekly self-report diaries. This was augmented by physiotherapist verification of dosing within formal and structured rehabilitation sessions throughout the assessment period. Patients were asked to record the number and type of rehabilitation sessions completed each day and the total daily time spent performing physical activity [refer to Figure 3.10; and Figure 3.11 for example]. Patients were not given feedback of results until after the completion of the prescribed number of test occasions.

<table>
<thead>
<tr>
<th>WEEK 4</th>
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<tbody>
<tr>
<td>Mon</td>
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<td>Sat</td>
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<td>Sun</td>
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</tbody>
</table>

**COMMENTS:** [Include comments regarding how motivated, positive, etc. or worried, frustrated, etc. you feel. Also add how much pain, discomfort, swelling, etc. you are experiencing. Document how active you have been during the day, for example how much walking, standing, you have done and when you return to work how physical your day has been, or how long you have to sit at a desk or spend driving when this becomes applicable. Please also note anything else you think may be relevant.]

**Figure 3.10** A blank example of a patient’s post-operative rehabilitation diary with suggested rehabilitation training to be completed - Week 4. The patient was instructed to tick or cross-out (giving explanations where possible) if they had achieved the suggested rehabilitation. The patient also documented the intensity, duration and volume where appropriate.
Figure 3.11 An anonymised example of an extracted page form a completed post-operative rehabilitation diary – Week 4.

3.4 Assessment occasions and procedures

In brief, this was an exploratory and feasibility study comparing the effects of a novel post-surgical rehabilitation comprising non-concurrent strength and endurance conditioning with two conditions of control within contemporary clinical practice (matched versus minimal assessment interaction) on functional, musculoskeletal and neuromuscular fitness. The experimental design examined group mean responses within the early, intermediate and longer-term phases (1-year follow-up) of ACL recovery in patients. The timing of post-surgery testing occasions was designed to correspond to and best-reflect, the most rapid period of physical improvement and effect sizes associated with the rehabilitation process. The experimental design comprised a longitudinal comparison of performances associated with the leg undergoing surgery with those of the contralateral control limb during the phases of recovery. The protocol is illustrated schematically in Figure 3.12.
The first assessment session included time for patients to become familiarised with the assessment procedures and protocols and was devised to obtain baseline pre-surgery measures of knee stability and perceived knee function. The initial meeting was with the researcher (~2 weeks prior to surgery) and then subsequent assessment sessions were conducted at 6 weeks, 12 weeks, 24 and 48 weeks following surgery. Patient reported outcome measures consisting of International Knee Documentation Committee (IKDC) subjective knee evaluation form, Knee injury and Osteoarthritis Outcome Score (KOOS) and Performance Profile (PP) were completed before the objective measures and in no particular order [refer to Appendices B, C and G for IKDC, KOOS and PP score forms, respectively]. The random sequence was decided upon by a computer generated programme. The order
of the objective functional outcome indicator, hop for distance (HOP) for both the injured and non-injured legs were determined in the same manner to ensure random ordering. The secondary objective outcomes of musculoskeletal and neuromuscular performance, anterior tibio-femoral displacement (ATFD), peak force (PF), rate of force development (RFD), electromechanical delay (EMD) and sensorimotor performance (SMP) associated with the knee extensors and flexors of the injured and non-injured legs, were assessed. The order of secondary objective assessments, leg to be tested first and for which muscle group, were also undertaken in a randomly-ordered sequence.

Prior to all testing sessions, patients undertook a standardised warm-up protocol that involved five minutes of cycle ergometry (90 watts for males, 60 watts for females, or as tolerated clinically by patients) and a further five minutes of static stretching of the involved musculature. Patients were then secured in a seated position on a custom-built dynamometer (Gleeson et al. 1992) and arthrometer (Gleeson et al. 1996b).

3.5 Self-perceived outcome measures

The self-perceived/ patient reported/ subjective outcomes used to assess functional performance in this study, were the International Knee Documentation Committee (IKDC) subjective knee evaluation form, the Knee injury and Osteoarthritis Outcome Score (KOOS) and a Performance Profile (PP) chart. The IKDC has been shown in previous investigative literature, to be valid and reliable. It was chosen as a primary indicator of subjective functional performance based on its relevance to the population addressed in this study (Harreld et al. 2006, Higgins et al. 2007, Hambly et al. 2010, Collins et al. 2011,
Irrgang et al. 2012). The KOOS score is a popular method of assessment of self-perceived functional outcome following ACL surgery. However, primarily the KOOS was developed to address chondral and arthritic knee pathology (Roos et al. 1998, Lohmander et al. 2004, Collins et al. 2011). This is significant to the ACL demographic as patients undergoing ACL injury increase the likelihood of developing osteoarthritis (Lohmander et al. 2004). The PP chart was added to the subjective assessment battery as unlike the IKDC score and KOOS, it measured constructs that were bespoke to the patient (Gleeson et al. 2008).

3.5.1 International Knee Documentation Committee (IKDC) subjective knee evaluation form

The IKDC is a widely-used and endorsed inventory that collects demographic information, a current health assessment and a subjective knee evaluation and which includes evaluations of subjective assessment of symptoms, capability for participation in sports activities, and functionality associated with the knee joint [see Appendix B – International Knee Documentation Committee (2000) subjective knee evaluation form] (Irrgang et al. 2001, Collins et al. 2011, Irrgang et al. 2012). In addition, it is a recognised knee score recommended by the National Knee Ligament Registry (http://www.uknlr.co.uk). This is a national database developed by a group of core surgeons and approved by the specialist bodies; British Association of the Knee (BASK), British Orthopaedic Sports Trauma and Arthroscopy Association (BOSTA) and the British Orthopaedic Association (BOA). The aim of the database is to ensure quality of surgical care following ACL injury and subsequent surgery enabling ‘national’ comparisons of outcomes.
The IKDC form employed in this study consists of 18 knee-specific questions or rated statements. The question that requires the patient to score their knee function prior to surgery is not included in the overall score. On the day of the assessment, patients were asked to complete the IKDC and on average, this took 5 – 10 minutes. The assessor answered any queries regarding any terminology or wording that the patient did not understand, but the assessor did not suggest how the patients should score or rate themselves.

The specific areas the IKDC addresses are:

(i) Symptoms, including pain, swelling, locking, catching and instability

(ii) Sports activities, ranging from strenuous activities like skiing and tennis to tasks of daily living such as rising from a chair and ascending or descending stairs

(iii) Rating current function compared to 'normal'.

The items are then scored using the equation:

\[
\text{IKDC Score} = \left( \frac{\text{Sum of Items}}{\text{Maximum Possible Score}} \right) \times 100
\]

For example, if the patient completed the form fully and the sum of scores for the 18 items was 45, the IKDC score would be calculated as:

\[
\text{IKDC Score} = \left( \frac{45}{87} \right) \times 100
\]

\[
\text{IKDC Score} = 51.7
\]
From this calculation, a patient scoring 0 would be considered as experiencing extreme knee problems and a patient scoring 100 would be considered to have no knee problems at all.

The IKDC subjective knee evaluation form can be calculated even if some items are missing, however up to 90% must be completed for scores to be valid (i.e. responses for 16 items are the minimum required). This is calculated by (the sum of the completed items) ÷ (the sum of the completed items) x 100. None of the patients assessed who completed this 48 week study, failed to respond to 100% of the IKDC form.

3.5.2 Knee injury and Osteoarthritis Outcome Score (KOOS)

The KOOS score is commonly used in assessing the health of the knee. It was specifically developed to address problems associated with arthritis as well as injury to the knee (Roos et al. 1998, Lohmander et al. 2004, Collins et al. 2011). This score like the IKDC is endorsed by the National Knee Ligament Registry (http://www.uknlr.co.uk).

On the day of the assessment, patients were asked to complete the KOOS form. The approximate time to complete the KOOS form was 5 – 10 minutes. Once again, the assessor explained any queries regarding any terminology or wording the patient did not understand, but the assessor did not suggest how the patient should score or rate themselves.

The KOOS knee survey is separated into 5 domains containing 42 items. Each domain is scored separately. A Likert scale is used for each item with 5 possible answers scoring 0 for no problems to 4 for extreme problems. Each of the 5 scores is calculated as the sum of each domain.
The domains are:

(i) Symptoms (7 items), including swelling, catching, grinding, range of movement and stiffness, etc.

(ii) Pain (9 items), including frequency and severity when performing tasks like walking, sitting and twisting, etc.

(iii) Functions of daily living (17 items), including stairs, dressing, bathing, etc.

(iv) Functions of sports and recreation (5 items), including running, kneeling, jumping and squatting, etc.

(v) Quality of life (4 items), including lifestyle modification and confidence, etc.

To calculate the KOOS score for pain, for example, the following equation was applied:

\[
\text{KOOS Pain} = \left( \frac{\text{Mean Score of Pain items} \times 100}{4} \right) - 100
\]

The other domains were calculated in the same manner. The individual mean scores for each separate domain were all divided by 4 as this was the maximum score for each item. From this calculation, a patient scoring 0 would be considered as experiencing extreme knee problems and a patient scoring 100 would be considered to have no knee problems at all.

In addition, if a patient inadvertently placed a mark outside an assigned item score box the closest box, was chosen and if two boxes were ticked, the most severe was reported as per the KOOS instructions. With respect to missing data, the mean score of each independent domain can still be calculated unless 50% or more of the items within a domain is missing. If this
occurred, the score for that domain would have been classed as invalid. However, no missing data was identified for the patients who completed study.

3.5.3 Performance profiling of self-perceived knee function (PP)

The concepts and the methodology of performance profiling were introduced to each patient within the 2 week period prior to ACL reconstruction surgery during an individual consultation. The same researcher delivered this introduction to all patients to ensure consistency. In accordance with the original protocols and procedures described by Butler and Hardy (1992), an individualised performance profile was elicited. Using this method of assessment allowed clarification of each patient’s self-perception of physical needs that each patient perceived to be important for the successful rehabilitation of his or her knee in order to return to optimal functioning. However, the procedures presented were adopted and modified to suit this clinical investigation (Gleeson et al. 2008). Butler and Hardy’s (1992) performance profiling methodology has since become a template from which a variety of alternative questions have since followed to elicit a performance profile, and of which have been adapted to suit the nature of the research (Weston et al. 2005). For example, each patient was asked to consider the question, “In your opinion, what are the main concerns you have with respect to your injured knee, what is stopping it from feeling normal?” If patient’s were unable to identify ‘constructs’, the researcher would ask questions to probe the patient to initiate constructs that were suitable. It has been suggested that prompts from the practitioner can assist the process of bringing personal ‘constructs’ into consciousness (Butler and Hardy 1992). In most circumstances, little prompting was required; however, for some participants, it
was necessary to illustrate examples of completed performance profiles. Bannister and Fransella (1986) suggested retaining generated constructs using participant’s own wording and terminologies. Therefore, if a patient selected a construct listed from an example performance profile shown, the patient had the opportunity to revise this construct using their own terminology and meaning of the selected construct. It was explained that there were no correct or incorrect answers and that the use of the performance profile was to attempt to discover what each patient considers important to himself/herself.

Following a discussion with the patient regarding the generated constructs, the performance profile chart was completed by mapping the patient’s constructs onto the perimeter of the performance profile chart. All of the generated constructs were retained on all performance profile charts throughout the period of the study. A variety of personalised constructs that patients perceived to be important to accomplish a full recovery were generated. Examples of constructs produced included physical descriptions and variations of the following elements: “pain,” “stability,” “support,” “strength,” “range of motion,” “giving away,” “change direction,” “endurance,” “swelling,” “stiffness,” “confidence,” “clicking,” “grinding,” “bruising,” “numbness,” “balance,” and “coordination.”

Once constructs had been elicited, patients were required to perform a self-assessment of the identified constructs. All patients were asked to consider, “How does your injured limb feel at the present time compared to your non-injured limb on each of the qualities you have listed?” Patients record their responses by shading an area of the profile corresponding to a one to ten scale, “extremely different to non-injured limb” (1) to “the same as my non-injured limb” (10) [see Figure 3.13]. An average score of knee function was calculated by
summating the scores (maximum score 10) for each construct on the profile chosen by the patient, and then dividing by the total number of constructs.

Figure 3.13 Completed performance profile with the qualities the participant perceives to be in need of rehabilitation and improvement displayed around the perimeter of the profile. Note: Shaded area represents perceived current state of the injured limb on scale of 1) "extremely different to non-injured limb" to 10) "the same as non-injured limb."

3.6 Patient and dynamometer orientation

Patients were secured in a seated position on a custom-built dynamometer (Gleeson et al. 1992, Minshull et al. 2007) and arthrometer (Gleeson et al. 1996b) [Figures 3.9.5 and 3.9.6], this device has been shown to
be a reliable and valid means of assessment (Gleeson et al. 1992, 1996b). The lever-arm on the dynamometer was attached to each leg in turn by means of padded ankle-cuffs and adjustable strapping, proximal to the lateral malleolus. The dynamometer and knee joint’s axes of rotation were aligned as closely as possible. Adjustable strapping across the mid-thoracic spine, pelvis and posterior thigh proximal to the knee localised the action of the involved musculature. A functionally relevant knee flexion angle of 25 degrees (0.44 rad), (0° = full knee extension) associated with the greatest mechanical strain on key ligaments (Li et al. 1999, Duthon et al. 2006, Renstrom et al. 2008, Alentorn-Geli, 2009), was identified for each patient during activation of the involved musculature using a goniometer system and was maintained throughout testing.

Figure 3.14 Schematic of participant and dynamometer orientation (adapted from Gleeson et al. 2008).
*Measurement of ACL laxity.
†Measurement of neuromuscular performance.
3.7 Objectively-measured outcome of function

3.7.1 Hop for distance

Single leg hop tests (HOP) are widely used by clinicians to determine knee function and are used as a method to assess return to sport following knee surgery (Clarke 2001, Hopper et al. 2002, Gustvasson et al. 2006, Reid et al. 2007, Thomeé et al. 2011). For the purpose of this study, hop for distance was identified to be the most relevant for the ACL population and availability of assessment space. The patients were required to start from a single leg stance on their assessed limb, before producing a hop for maximum distance with a controlled landing, in a stable position. No restriction was placed on arm movement, in order to provide assistance with balance, if required. Distance was measured in centimetres from the toe at the start position to the heel at the landing position. Following two to three practice
attempts, participants performed three maximal efforts, with the mean of the inter-trial replicates subsequently used for analysis.

3.8 Objectively-measured outcomes of musculoskeletal and neuromuscular performance

3.8.1 Anterior tibio-femoral displacement (ATFD)

Assessment of anterior tibio-femoral displacement (ATFD) was undertaken in the injured and contralateral (non-injured) legs (Gleeson et al. 1992). The arthrometer system used in this assessment has been shown to be reliable and valid (Gleeson et al. 1996b). The apparatus and patient orientation during the assessment is shown schematically in Figure 3.13. The knee joint was maintained at 25 degrees (0.44 radians) of flexion with foot positioning at 15 degrees (0.26 radians) of external rotation and 20 degrees (0.35 radians) of plantar flexion. Instrumentation to measure ATFD consisted of two linear inductive displacement transducers (DCT500C, RDP Electronics Ltd., Wolverhampton, U.K.: 0.025m range). The latter incorporated spring-loaded plungers that were adjusted accurately in three planes to provide perpendicular attachment to the patella and tibial tubercle. During measurements, both transducers were secured to the skin surface using tape and able to move freely only in the anterior-posterior plane relative to the supporting framework. The instrument monitored only the relative motion between the patella and tibial sensors and so facilitated the exclusion of measurement artefacts caused by extraneous movements of the leg during the application of anterior displacement forces. Anterior force was applied in the sagittal plane and in a perpendicular direction relative to the tibia by an instrumented force-handle.
incorporating a load cell (Model 31E500N0, RDP Electronics Ltd., and Wolverhampton, U.K.: range 500N). This device was positioned behind the leg at a level 0.02m inferior to the tibial tubercle. The transducers were interfaced to a computerised data acquisition system (Cambridge Electronic Design Ltd., U.K.). Calibrated data from all transducers were sampled at 2.5 kHz.

Measurements on each knee were preceded by two practice trials. During each measurement, patients were instructed to relax the musculature of the involved limb. The latter was verified by inspection of on-line EMG records of the activity of m. biceps femoris and m. vastus lateralis. Rapid but gentle manual anterior-posterior drawer oscillations were used to facilitate relaxation and to establish a neutral tibio-femoral position from which all measurements were initiated. The same test administrator performed all measurements. Indices of ATFD were calculated as the mean of three intra-session replicates of the net displacement of the patella and tibial tubercle transducers at an anterior tibial displacement force of 160N applied in the sagittal plane, at a rate of $67 \pm 7 \text{ N} \cdot \text{s}^{-1}$, and this procedure was tolerated well by symptomatic patients (Gleeson et al. 1992, Gleeson et al. 2008).

### 3.8.2 Maximal voluntary muscle activation (MVMA)

Following a series of sub-maximal warm-up muscle activations (two efforts at 50% self perceived force, two efforts at 70% self perceived force and one effort at 90% perceived force), an auditory signal was given randomly within 1-4 seconds that instructed the patients to flex the knee joint as rapidly and forcefully as possible against the immovable restraint offered by the apparatus, providing a maximal voluntary muscle activation [MVMA]. Another auditory signal was given to the patient after 3-seconds of MVMA to cue neuromuscular relaxation. Intra-
trial MVMA replicates were each separated by at least 10-seconds (Moore et al. 1991, Gleeson et al. 1996b, Minshull et al. 2009, Minshull et al. 2011). The MVMA of the knee extensor musculature was achieved in a similar manner.

3.8.3 Peak force (PF), rate of force development (RFD) and electromechanical delay (EMD)

Electromyographic activity (EMG) was recorded from the m. biceps femoris during the estimation of volitional static flexion peak force (PF) using bipolar rectangular surface electrodes (self-adhesive, Ag/AgCl; 10 mm diameter; Unilect, UK) that were applied longitudinally over the belly of the muscle parallel to the orientation of the muscle fibres. Similar EMG records were obtained from the m. vastus lateralis during the estimation of volitional static extension PF. The raw unfiltered EMG signals, which incorporated minimal intrusion from induced currents associated with external electrical and electromagnetic sources and noise inherent in the remainder of the recording instrumentation, were passed through a differential amplifier (input impedance 10,000 MΩ, CMRR 100 dB, gain of 1000), filtered (Butterworth 2\textsuperscript{nd} order; 1kHz cut-off frequency) [Cambridge Electronic Design, UK]) and were analogue-to-digitally converted at 2.5kHz sample rate, ensuring a significant margin of reserve between the highest frequency expected in the EMG signal and the Nyquist frequency (Gleeson et al. 2001). The inter-electrode distance was 30 mm and a reference electrode was placed 30mm lateral and equidistant from the recording electrodes [Figures 3.16 and 3.17]. Standardised skin preparation techniques yielded inter-electrode impedance of less than 5kΩ. Electrode placement was standardised across inter-day testing by marking the skin with indelible ink and mapping to anatomical landmarks. The m. biceps femoris and
m. vastus lateralis were selected as important contributors to anterior tibiofemoral displacement and lateral rotation of the femur relative to the tibia since both processes have been implicated in ACL injury (Li et al. 1999, Myer et al. 2005, Renstrom et al. 2008, Alentorn-Geli, 2009).

The index of PF was recorded as the mean of the highest force response during three MVMA intra-trial replicates. Volitional RFD was calculated as the average rate of force increase between 25% and 75% of PF. Volitional EMD was computed as the mean response of three intra-trial muscle activations in which the time delay between the onset of electrical activity and the onset of force was recorded. Onset of electrical activity and muscle force was defined as the first point in time where the recorded signals exceeded consistently the 95% confidence limits of the background electrical noise amplitude (Bell et al. 1986, Minshull et al. 2009, Minshull et al. 2011) [Figure 3.18].
3.8.4 Force error (FE) and sensorimotor performance (SMP)

Sensorimotor performance (SMP) was assessed as the ability to scale volitional force precisely (Baltzopoulos et al. 2001) and measured as the force error (FE) arising from a task that required the ‘blinded’ replication using the knee flexors of a target force (50 % of pre-operative of PF). The task was a slow, self-regulated muscular activation (at a rate of ~200N·s⁻¹) with a standardised delay between the presentation of target and response (10s). The extent of FE describes the bias or constant error around a target force and lower scores reflect better sensorimotor performance. Each assessment occasion included a familiarisation session of 15 practice efforts, in which each
participant was familiarised with 50% of his/her pre-operative PF in a ‘blinded’ fashion (Pincivero et al. 2000). Participants were blinded to both the absolute level of the prescribed target force and the scale of measurement used to offer feedback. Feedback from the test administrator was offered in a standardised, arbitrary scale of measurement without units using terminology such as “20 high”, “5 high” and “25 low”, “15 low”, respectively, depending whether or not the outcome of a trial had been higher or lower than the target. Trials that showed outcomes that were within ± 2.0N of the target force (99% confidence limits of the technical error associated with the load cell) were described in feedback to the participant as having “no error”. The patients indicated reproducing the target force precisely during assessments by fully relaxing the knee flexor or extensor musculature. For any given performance trial, force error in performance was computed using the generic expression: 

\[
\text{force error} = \frac{[\text{observed performance score} - \text{target performance score}]}{\text{target performance score}} \times 100\%.
\]

The mean error of three trials was used for subsequent data analysis.

3.9 Statistical analyses

3.9.1 Statistical analyses - randomised controlled study

[Chapters 4 and 5]

The clinical efficacy of non-concurrent conditioning was assessed using separate analyses of variance (ANOVAs) for each primary outcome measures of function (IKDC, KOOS, PP, HOP) and the secondary musculoskeletal and neuromuscular performance outcomes of anterior tibio-femoral displacement (ATFD), peak force (PF), electromechanical delay (EMD), rate of force
development (RFD), and sensorimotor performance (SMP). The ANOVA model involving factors of group (NCON; CON) by leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) with repeated measures on the latter two factors was used to test the null-hypothesis of no statistical interaction between the mean group responses of patients undertaking non-concurrent and current rehabilitation conditioning over time for outcomes that had assessed the performance of each leg separately. An ANOVA model using factors of group (NCON; CON) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) with repeated measures on the latter factor was used to test the equivalent null-hypothesis for outcomes in which the assessment of separate leg performance had not been required (IKDC and KOOS) or in which the non-injured leg had been used as a routine comparator (PP). The outcome performances associated with the knee extensors and flexors of both injured and non-injured legs were assessed separately, where appropriate.

The potential influences on function, musculoskeletal and neuromuscular performance of clinico-social approbation by patients associated with increased assessment administrator-patient interactions were assessed using separate ANOVAs involving factors of group (NCON; CON [matched assessor-patient interaction with experimental condition]; Limited testing CON [minimal assessor-patient interaction compared to experimental condition]) by test occasion (pre-surgery versus 48 weeks post-surgery) with repeated measures on the last factor.
3.9.2 Statistical analyses – correlations between subjectively-measured and objectively-measured outcomes [Chapter 6]

In order to explore the relationships between the selected subjective measure of knee function (IKDC) and the objective measure of function (HOP) and indices of musculoskeletal and neuromuscular performance recorded at baseline (≈2 weeks prior to surgery) and at 24 weeks post ACL surgery were considered for analysis.

Firstly, relationships amongst subjective and objective outcome measures of function, and outcomes of musculoskeletal and neuromuscular performance involving absolute scores of the injured leg, were assessed as follows: IKDC and single-leg hop and between IKDC and anterior tibio-femoral displacement, peak force, electromechanical delay, rate of force development, and force error scores at the pre-surgery and 24 weeks post-surgery assessment occasions.

Secondly, relationships amongst subjective and objective outcome measures of function, and outcomes of musculoskeletal and neuromuscular performance involving injured-contralateral legs were assessed as follows: Difference scores associated with injured-contralateral leg functional or performance comparisons at each assessment point and relativised to the performance score of the non-injured leg at pre-surgery were used to compute correlation coefficients (Pearson product-moment) amongst outcome variables of IKDC, single-leg hop, anterior tibio-femoral displacement, peak force, electromechanical delay, rate of force development, and force error scores.

Thirdly, relationships amongst subjective and objective outcome measures of function, and outcomes of musculoskeletal and neuromuscular performance associated with changes in absolute scores for the injured leg from
pre-surgery to 24 weeks were assessed as follows: The potential for relationships associated with the rehabilitation-related patterns of change amongst outcome variables was assessed by computing correlations (Pearson product-moment) involving the difference score for each outcome between pre-surgery and at 24 weeks post-surgery, with relativisation to the performance score of the non-injured leg at pre-surgery, where appropriate (i.e. in those indices offering data for each leg).

Two-tailed probabilities were used due to the exploratory nature of this study and potential for both differing timing of performance and functional losses and gains amongst the outcomes over the follow-up period (Gleeson et al. 2008).

3.9.3 Power calculation

A priori alpha levels were set at $p<0.05$. The experimental design offered an approximate 0.70 power of avoiding a Type-II error when employing a least detectable difference of 0.2 mm, 16N, 40N·s$^{-1}$, 4ms, 2.5%, 0.5 units, 0.5 units and 0.3 units during comparisons of ATFD, PF, RFD, EMD and SMP, and PPT, KOOS sand IKDC scores over time, respectively (Lipsey 1990). These estimates, associated with Chapters 4 and 5, were based on expectations for ‘minimum’ sample size (n=60 patients meeting the inclusion criteria), randomly-allocated to the main experimental and control groups, that had received favourable ethical opinion previously (Shropshire Area NHS Ethics Committee [REC reference 05/Q2601/36]). Where selected assumptions underpinning analysis of variance had not been met, Greenhouse-Geisser adjustments of the degrees of freedom associated with the experimental and error variances were used.
Chapter 4:

Effects of Anterior Cruciate Ligament Reconstruction Surgery and Non-Concurrent Strength and Endurance Rehabilitation on Self-Perceived Function
4.1 Chapter abstract

Title: Effects of anterior cruciate reconstruction surgery and non-concurrent strength and endurance rehabilitation on self-perceived function: A prospective, random-allocation controlled study.

Context: The anterior cruciate ligament (ACL) provides stability to the knee. Therefore, injury to the ACL can have a serious impact on functional activity. Unfortunately, following ACL reconstructive surgery, discrepancies when it is safe to return to full sporting function exist. Self-perceived/ patient reported outcome measures are commonly used to assess levels of subjective function following ACL surgery and subsequent rehabilitation. Yet, despite evidence in healthy populations pertaining to the attenuation of strength gains caused by concurrent training, ACL rehabilitation is traditionally prescribed and administered in a concurrent format. Therefore, it is possible that structuring rehabilitation in a non-concurrent fashion will improve functional performance.

Objective: The purpose of this randomised control trial was to assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on self-perceived outcome measures of function (IKDC, KOOS, PP) in patients with anterior cruciate ligament deficiency. Setting: Orthopaedic Hospital NHS Foundation Trust. Design: Prospective random-allocation to group trial involving iso-volume rehabilitative intervention versus contemporary practice, using contralateral limb assessment and clinico-social approbation controls. The design compared the effects of experimental post-surgical rehabilitation comprising non-concurrent strength and endurance conditioning with two conditions of control reflecting contemporary clinical practice (matched versus
minimal assessment interaction). **Participants:** Eighty two patients (69♂, 13♀, age: 35.4 ± 8.6 yr; time from injury to surgery 9.4 ± 6.9 months [mean ± SD]) electing to undergo unilateral ACL reconstructive surgery (semitendinosus and gracilis graft [n = 57]; central third, bone-patella tendon-bone graft [n = 25]) were randomly allocated to groups (2:2:1 purposive sampling ratio, respectively). Nineteen patients were lost to follow-up. **Intervention:** A patient group following a standardised traditional concurrent (CON) ACL rehabilitation programme acted as the control versus a group following an experimental non-concurrent (NCON) ACL rehabilitation programme that involved separation of strength and cardio-vascular endurance conditioning. An additional control group (Limited testing CON) matched the CON group rehabilitation applied within contemporary clinical practice. **Main Outcome Measures:** The self-perceived primary outcome measures of function were IKDC, KOOS and PP were assessed on five separate occasions (pre-surgery, and at 6, 12, 24 and 48 weeks post-surgery). However, assessment occasions were purposefully reduced to pre-operative and at 48 weeks post-operative only for the Limited testing CON group. **Results:** Factorial analyses of variance (ANOVAs) with repeated-measures showed significant group (NCON; CON) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) interactions for outcomes of self-perceived function IKDC, KOOS and PP confirmed increased clinical effectiveness of NCON conditioning ($F_{(2.0, 82.9)} = 4.0 \ p<0.05$, $F_{(2.2, 134.7)} = 5.5 \ p<0.001$, $F_{(1.9, 121.4)} = 14.6 \ p<0.001$, respectively) and the group mean peak relative difference in improvement for NCON was ~5.9% - 12.7% superior to CON. The greatest interaction effect was found to occur between pre-surgery and the 12 weeks post-operative test occasion for IKDC and KOOS, and between pre-surgery and the 24 week test occasion for PP. Patterns of
improvements in self-perceived fitness over time were represented by a relative effect size range of 0.71 to 1.92. Improvement patterns were not significantly different between control groups offering matched or minimised assessor-patient interaction (CON vs. Limited testing CON; pre-surgery versus 48 weeks post-surgery) indicating that clinical approbation by patients had not contributed to the outcome. **Conclusion:** Overall, the patterning and extent of changes amongst subjective functional performance scores offer support for the efficacy of using NCON strength and endurance conditioning to enhance post-surgery rehabilitation.
4.2 Introduction

The knee is one of the most commonly injured joints and the anterior cruciate ligament (ACL) accounts for approximately 46% of all ligamentous injuries, surgery to reconstruct this ligament is relatively common-place (Bollen 2000, Renstrom et al. 2008, Dallalana et al. 2011). The subsequent rehabilitation following ACL reconstruction surgery at takes approximately 6 – 9 months (Kvist 2004, Beynnon et al. 2005, Grinsven et al. 2009, Trees et al. 2009, van Grinsven et al 2010, Lobb et al. 2012, Manske 2012). Despite the notion that advances in ACL surgery and rehabilitation no longer cause a threat to the restoration of full function (Bjordal, 1997), more recent literature suggests that this might not be the case (Ardern 2011a, 2011b). Ardern et al. (2011a) reports failure to restore functional capability in the knee up to 12 months post-surgery occurs in 67% of ACL patients. Additionally, a meta-analysis investigating the return to sport following ACL injury found that 15% of patients did not return to perceived levels of normal levels of activity when measured using the patient reported International Knee Documentation Committee subjective evaluation form (IKDC) (Ardern 2011b). Therefore, a better understanding of when it is safe to return to function following rehabilitation for this prevalent ACL population is of clinical and social significance. Especially as the consequences of ACL injury and time to return to full function can incur direct (surgery, medical care, management and rehabilitation) and indirect (time lost from work, decreased productivity) costs (Zelle at al. 2005, Paxton at al. 2010).

Following ACL reconstructive surgery, physiotherapy rehabilitation is offered in a concurrent format, whereby strength and endurance exercises are performed within the same rehabilitation session. For many decades, it has

There are discrepancies of understanding amongst research findings in the literature that have been generated by different types of strength training, experimental designs, strategies for subject sampling, designs of training programme and sensitivities associated with the dependent variables of interest. Nevertheless, it is now a longstanding belief in the field of sports and athletics, that concurrent training compromises strength gains (Wilson 2012).
Therefore, there is a potential for attenuation of strength gains during any period of rehabilitation brought about by the contemporary rehabilitative practice of concurrent conditioning. However, no study to date has investigated the potential interference effect of concurrent training in injured or post-operative populations. Clearly, there is a gap in the literature for a randomised controlled and iso-volumetric study investigating and comparing the effects of concurrent with non-concurrent conditioning in injured or post-operative patients.

A number of self-perceived (patient-reported) outcome measures exist specifically designed to evaluate knee function, for example, the International Knee Documentation Committee (IKDC) subjective knee evaluation measure, the Knee injury and Osteoarthritis Outcome Score (KOOS), the Knee Injury and Osteoarthritis Outcome Score Physical Function Short Form (KOOS-PS), the Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL), the Lysholm knee scoring scale, the Oxford Knee Score (KOS), the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the Activity Rating Scale (ARS) and the Tegner Activity Score (TAS). All of these measures are used within orthopaedics and/or rheumatology to measure the patient’s self-perception of pain, function, quality of life, activity levels, etc. Most of these scores are used to assess a variety of knee conditions, including osteoarthritis, patellofemoral problems, chondral lesions, meniscal injury or following arthroplasty, for example. Of these commonly used scores, the most relevant to ACL injury have been shown to be IKDC and KOOS. Figure 4.1 summarises the strengths, cautions, clinical utility and research usability of popular self-perceived measures applicable to ACL populations, based on a review of the most recent literature by Collins et al. (2011).
Figure 4.1: Self-perceived outcome scores (Selection based on a review of measures of knee function [Collins 2011]).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Strengths</th>
<th>Cons</th>
<th>Cautions</th>
<th>Clinical Utility</th>
<th>Research Usability</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKDC</td>
<td>Elements important to patients</td>
<td>Consistent</td>
<td>Use of one aggregate score</td>
<td>Minimal administration</td>
<td>Supported</td>
</tr>
<tr>
<td>KOOS</td>
<td>Substantial psychometric testing</td>
<td>Reliable and valid</td>
<td>Rach analysis suggests some subscales exhibit unidimensionality in ACL-R patients</td>
<td>Sport/recreation subscale not as reliable</td>
<td>Can be compared with WOMAC subscales</td>
</tr>
<tr>
<td>Lysholm</td>
<td>Detects change in surgical and non-surgical</td>
<td></td>
<td>Content validity cannot be assumed</td>
<td>Reliably tracks change over time</td>
<td>Consistently use the same scale version</td>
</tr>
<tr>
<td>WOMAC</td>
<td>Substantial psychometric testing</td>
<td>Reliable and valid</td>
<td>Was developed as an adjunct to the Lysholm, not a standalone measure</td>
<td>Adequate reliability for some individuals</td>
<td>More appropriate for within subject repeated measures studies rather than between group comparisons</td>
</tr>
<tr>
<td>TAS</td>
<td>Considers influence of activity level on symptoms</td>
<td></td>
<td>Increased chance of interviewer bias</td>
<td>Lacking psychometric testing</td>
<td>More appropriate for within subject repeated measures studies rather than between group comparisons</td>
</tr>
<tr>
<td>ARS</td>
<td>ICC 0.97</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

* = ACL populations

Applicable for this study
The IKDC subjective evaluation score is a valid and reliable measure (ICC 0.9 – 0.95). It was designed to detect improvement or deterioration in symptoms including pain, swelling, locking, catching and instability (Irrgang et al. 2001, Harreld et al. 2006, Higgins et al. 2007, Collins et al. 2011, Irrgang et al. 2012). It addresses self-perceived levels of sporting activity and allows the patient to rate how ‘normal’ his/her knee is. The IKDC (patient-reported) scoring system is a widely used subjective measure and is endorsed by the International Cartilage Repair Society (ICRS), European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA), the American Orthopaedic Society for Sports Medicine (AOSSM) and more recently the National Knee Ligament Registry (NKLR). The respondent, administrative and cost-burden is minimal, requiring approximately 15 minutes in total.

In comparison, the KOOS outcome score assesses not only symptoms associated with ligamentous disruption, but it also detects self-perceived changes related to arthritic change (Roos et al. 1998, Lohmander et al. 2004, Collins et al. 2011). It is widely acknowledged that patients who have suffered an ACL injury are more likely to develop osteoarthritis. Therefore, the inclusion of this measure for the ACL population is justified (Roos et al. 1998, Lohmander et al. 2004, Collins et al. 2011). The KOOS outcome score is a valid and reliable measure with intra-class correlations ranging from 0.6 – 0.95 (Collins et al. 2011). The content of the KOOS is split into 5 domains addressing pain, symptoms, activities of daily living, recreation and sports and quality of life. It has a similar respondent and administrative burden as the IKDC (15 minutes). The KOOS is also endorsed by the ICRS, AAOS, NKLR and the US Food and Drug Administration.
However, both the IKDC and KOOS outcome scores, by design, are restricted to set questions and patient rated scales; as such they might not assess a patient's individual concerns. Therefore, the use of performance profile (PP) technique, which is based on the personal construct theory (Kelly 1955), was thought to be a useful adjunct to the IKDC and KOOS in this study. The PP technique allows the patient to devise a visual scale of personal outcome measures that highlight key areas of concern, specific to that patient. The clinician can discuss the identified constructs with patient and focus the rehabilitation to the areas considered important. The PP technique empowers the patient to have an active role in the decision-making process of their rehabilitation. Documenting what the patient perceives to be important factors required to establish normal function, might in turn, increase the patient's compliance to rehabilitation. In addition, the PP technique can also be used as a tool to monitor change in self-perceived (subjective) function during a period of rehabilitation (Doyle 1998).

Additionally, a patient’s perception of capability might be biased when scaling subjective scores via interaction with the assessor. The influence of the assessor on patients through clinical and social approbation, might be substantive and possibly bias the subjective outcomes. For this reason the experimental design for the research used in this thesis includes an additional ‘control’ (Limited testing NCON). The assessor influence is quantified by purposefully considering the net effects of minimised and maximised assessor-patient interactions within the experimental design.

The purpose of this randomised control trial was to assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on self-perceived outcome
measures of function (IKDC, KOOS, PP) in patients with anterior cruciate ligament deficiency. In addition, the possibility of clinico-social approbation brought about by assessor-patient interaction was assessed.

It was hypothesised that significantly enhanced self-perceived (subjective) functional gains measured using IKDC, KOOS, PP, will be accomplished by rehabilitating from ACL surgery over time in a NCON format compared to the traditional phasing of concurrent (CON) conditioning.

Therefore, the following chapter describes a prospectively randomised control trial, investigating the effects of reconstruction surgery and non-concurrent strength and endurance (NCON) rehabilitation on self-perceived function in patients with anterior cruciate ligament-deficiency.
4.3 Methods summary

4.3.1 Participants

Eighty two patients (69 males [age: 35.4 ± 8.6 yr (range 19 to 50 yr); height = 1.79 ± 0.07 m; body mass = 83.6 ± 11.4 kg; time from injury to surgery 9.4 ± 6.9 months [mean ± SD]; 13 females [age: 41.6 ± 7.6 yr (range 36 to 49 yr); height = 1.68 ± 0.09 m; body mass = 69.7 ± 10.7 kg; time from injury to surgery 6.4 ± 4.9 months]), electing to undergo unilateral ACL-reconstructive surgery (central third, bone-patella tendon-bone graft [n = 25], or semitendinosus and gracilis graft [n = 57]) at a U.K. National Health Service Foundation Trust hospital, gave their informed consent to participate in the study. Patients were treated by two consultant orthopaedic surgeons (DR; SR) of similar experience and practice (> 12 ACL reconstruction surgeries per month) using agreed and matched surgical procedures. Patients meeting inclusion criteria from a randomly-sequenced cohort awaiting surgery or subsequently presenting with injury, were offered participation.

Patients were approached who had consented for ACL autologous reconstructive surgery by one of the two surgeons involved in this study and who would have been willing to attend the Orthopaedic NHS Foundation Trust for rehabilitation. No exclusions were made regarding the autologous graft choice. The study was discussed with the eligible patient, including the potential risks and benefits and the Patient Information Sheet was issued [see Appendix E – patient participation sheet and Appendix F – thesis participation consent form]. The patients were contacted approximately one week after this initial meeting to be given the opportunity to ask further questions and to participate in the study. All participants were fully aware that they could
withdraw from the study without giving any reason and this would in no way alter the care they received. The inclusion exclusion criteria is summarised in Table: 4.1.

<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
</tr>
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<tbody>
<tr>
<td>Adults (&gt;16 yr)</td>
<td>Systemic pathologies</td>
</tr>
<tr>
<td>Mentally mature</td>
<td>Bilateral knee injuries</td>
</tr>
<tr>
<td>Consented to autologous ACL reconstruction surgery</td>
<td>Multiple ligament injuries</td>
</tr>
<tr>
<td>Under the surgical care of DR or SR</td>
<td>Declined to participate in the study</td>
</tr>
<tr>
<td>Available to attend the Orthopaedic NHS Foundation Trust for rehabilitation</td>
<td></td>
</tr>
<tr>
<td>Any ethnicity</td>
<td></td>
</tr>
<tr>
<td>Any gender</td>
<td></td>
</tr>
<tr>
<td>Consented to study</td>
<td></td>
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</table>

Table 4.1 Summary of the studies inclusion and exclusion criteria

4.3.2 Ethical approval

This study met the ethical standards suggested by Harriss and Atkinson (2009), and the study was approved by the Ethics Committee for Human Testing of the University of Exeter, UK, and by the Shropshire area NHS Ethics Committee (REC reference 05/Q2601/36) and had received scientific merit approval from the Research Committee of Orthopaedic NHS Foundation Trust, UK. The study can be tracked using the reference code R5613 with respect to The National Institute for Health Research (NIHR) Clinical Research Network (CRN).
4.3.3 Randomisation

Patients were prospectively randomised to one of three groups:

**CON** (n=31 [29♂, 2♀] [age: 37.5 ± 8.8 yr (range 19 to 50 yr); height = 1.77 ± 0.07 m; body mass = 81.4 ±12.3.0 kg; time from injury to surgery 9.4 ± 6.9 months]; n=9 lost to follow-up) comprising a standardised and established (>5 yr) programme of exercise rehabilitation used in current clinical practice (24 weeks of structured and supervised rehabilitation conditioning [705 ± 10 minutes]) focusing on progressive mobility, strength and endurance conditioning;

**NCON** (n=33 [27♂, 6♀] [age: 36.6 ± 9.0 yr (range 21 to 50 yr); height = 1.76 ± 0.09 m; body mass = 82.4 ± 11.1 kg; time from injury to surgery 8.3 ± 6.7 months]; n=7 lost to follow-up) comprising and matching the type, volume and intensity associated with the programme of exercise rehabilitation prescribed in CON, but modified to include the novel and specific phasing of strength and endurance exercises and designed to minimise physiological inhibition associated with concurrent strength and endurance conditioning.

**Limited testing CON** (n=18 [16♂, 5♀] [age: 34.2 ± 8.1 yr (range 23 to 50 yr); height = 1.79 ± 0.09 m; body mass = 81.1 ± 17.3 kg; time from injury to surgery 9.1 ± 7.2 months]; n=3 lost to follow-up) matching the programme of exercise rehabilitation used in CON but with purposeful minimised attention and assessor-patient interaction during rehabilitation outcome assessments other that at the recruitment to the study (pre-surgery) and at its completion (48 weeks post-surgery). This control condition was included to quantify the influence of the test administrator during assessment procedures and potential clinical and social approbation that might have been expected to enhance outcome.
The patient group allocation and flow through this study is summarised in the Consort Diagram [Figure 4.2].

All participants had been involved in recreational to high-level sports. Fifty-one percent of patients had presented with right knee injury, with 58.5% of patients reporting injury to the preferred leg. Eleven percent of patients had obtained the injury via normal activities of daily living; 65% patients had obtained the injury via a non-contact incident whilst performing sport, and 24% by means of a contact incident during sport. The mechanism of injury was categorised as either ‘contact’ or ‘non-contact’: ‘contact’ if there had been contact with another individual resulting in the injury, regardless of where on the body the contact had occurred.

### 4.3.4 Batch Allocation

Patients were sequentially batch-allocated in a randomised-fashion to groups (CON; NCON; Limited testing CON) using a purposive sampling ratio (2:2:1), respectively. This enabled optimisation of experimental design sensitivity amongst comparisons associated with the two primary ‘arms’ of the study (CON and NCON versus Limited testing CON).

### 4.3.5 Intention to treat

Patients lost to follow-up affected varying assessment sessions [Figure 4.2]. No secondary injuries occurred to any of the patients during the rehabilitation or assessment process. Therefore, secondary injury was not a contributing factor in lost to follow-up. However, as stated in the patient information (see Appendix E), patients who were lost to follow-up were not questioned as to why they chose to leave the study at a particular point,
although 10 of the 19 patients did voluntarily offer the reason of work/life commitments intruding on the time available to contribute to the research study.

The potential influences of bias and compromised external validity on this study’s findings associated with altered group composition and altered patterns of outcome data due to patients being lost to follow-up was assessed using separate ANOVAs for each outcome measure at baseline. These analyses incorporated the factor of group (NCON; CON; Limited CON; Lost to-follow-up). The lost to follow-up results are presented in Section 4.6.

All subjective outcomes were assessed at baseline. All the subjective outcomes showed statistically similar characteristics at baseline amongst the group mean scores for experimental groupings and those patients who had been lost to-follow-up. This suggested cautiously, that biasing of data might have intruded in only a minor way in this study.
Figure 4.2 Consort Diagram – summary of the number of patients recruited, the random allocation and those lost to follow-up associated with self-perceived (subjective) outcome measures of function following either CON or NCON ACL rehabilitation.
4.3.6 Intervention

A full and detailed description of the post-operative ACL rehabilitation followed by each group (CON, NCON and Limited testing CON) is found in Chapter 3 – Section 3.3.

In summary, all the groups followed the same rehabilitative guide [Appendix A - RJAH anterior cruciate ligament rehabilitation guide] with respect to the progression of activity and function. This is largely dictated by the healing process of the graft tissue. On average, it takes approximately 6 weeks to overcome the insult of the surgery with respect to activity and function. During this acute phase, rehabilitative exercises are progressed as the patients symptoms allow. For up to 3 months following surgery, physical restrictions are placed on performing open kinetic chain quadriceps exercises, running and twisting and turning on the knee. However, from this point, the restrictions no longer apply, with the exception of predictable twisting and turning type manoeuvres at speed, which was not formally introduced until 4 months after surgery, progressing to unrestricted agility from 5 months post-surgery. It is not until 6 months following ACL reconstruction that no physical restrictions are placed on the patients and full-contact sports are gradually introduced. However, traditionally ACL rehabilitation includes both heavy resistance exercises and cardio-vascular endurance exercises to be performed within the same treatment session (CON). The study intervention sequentially separated these exercises to different days (NCON). The intensity and volume across the groups was standardised over each month. In addition, to the clinical notes documenting each supervised rehabilitation session, patients also recorded their self-administered activity by means of a diary.
4.3.7 Experimental and assessment procedures

Patients were assessed on five separate occasions (pre-surgery, and at 6, 12, 24 and 48 weeks post-surgery) with the exception on Limited testing CON (pre-surgery and 48 weeks post-surgery). After surgery, all patients were treated and assessed by the same physiotherapist for the duration of their rehabilitation period.

The first assessment session included time for patients to become familiarised with the assessment procedure and was devised to obtain baseline pre-surgery measures of perceived knee function. During this initial meeting with the assessor (~2 weeks prior to surgery) and at subsequent assessment sessions (conducted at 6 weeks, 12 weeks, 24 and 48 weeks) following surgery, each patient was assessed for the self-perceived outcome of function (IKDC, KOOS, PP). The order of the completion for inventories was undertaken in a random sequence.

4.3.7.1 IKDC subjective knee evaluation form


To summarise, on the day of the assessment, patients were asked to complete the IKDC and on average this took 5 – 10 minutes. The assessor answered any queries regarding any terminology or wording that the patient
did not understand, but the assessor did not suggest how the patients should score or rate themselves.

The IKDC was calculated and a patient scoring 0 would be considered as experiencing extreme knee problems and a patient scoring 100 would be considered to have no knee problems at all. None of the patients assessed who completed this 48 week study failed to respond to 100% of the IKDC form.

4.3.7.2 KOOS outcome score

The KOOS score is commonly used in assessing the health of the knee [see Appendix C – Knee Injury and Osteoarthritis Outcome Score] (Roos et al. 1998, Lohmander et al. 2004, Collins et al. 2011). A detailed description of KOOS content and prescribed evaluative calculation can be found in Chapter 3 – Section 3.5.2.

To summarise, on the day of the assessment, patients were asked to complete the KOOS form. The approximate time to complete the KOOS form was 5 – 10 minutes. Once again, the assessor answered any queries regarding terminology or wording that the patient did not understand, but the assessor did not suggest how the patients should score or rate themselves.

From the KOOS calculation, a patient scoring 0 would be considered as experiencing extreme knee problems and a patient scoring 100 would be considered to have no knee problems at all. No missing data was identified for the patients who completed study.
4.3.7.3 PP technique

The PP technique has previously been used to assess clinical populations (Doyle et al. 1998) [see Appendix G – Performance Profile technique]. A detailed description of the PP administration and data extraction can be found in Chapter 3 – Section 3.5.3.

Following on from the first assessment when the individualised constructs were chosen and rated (0 – 10), the same constructs were used for the subsequent assessment occasions and rated in the same manner. An average score of knee function was calculated by summating the scores (maximum score 10) for each construct on the profile chosen by the patient, and then dividing by the total number of constructs.

4.3.8 Statistical analyses

The clinical efficacy of non-concurrent conditioning was assessed using separate analyses of variance (ANOVAs) for each self-perceived (subjective) outcome measure of function. The ANOVA model used factors of group (NCON; CON) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) with repeated measures on the latter factor. This was used to test the null-hypothesis of similar self-perceived (subjective) functional gains measured using IKDC, KOOS, PP, will be accomplished by rehabilitating from ACL surgery over time in a NCON format compared to the traditional phasing of concurrent (CON) conditioning.

The potential influences on self-perceived (subjective) function by clinical and or social approbation associated with increased assessment assessor-patient interactions was assessed using separate ANOVAs involving factors of group (NCON; CON [matched assessor- patient interaction with experimental
condition]; Limited testing CON [minimal assessor-patient interaction compared to experimental condition]) by test occasion (pre-surgery versus 48 weeks post-surgery) with repeated measures on the last factor.

A priori alpha levels were set at $p<0.05$. The experimental design offered an approximate 0.70 power of avoiding a Type-II error when employing a least detectable difference of 0.3 units, 0.5 units and 0.5 units during comparisons of IKDC, KOOS and PP scores over time, respectively (Lipsey 1990). Where selected assumptions underpinning analysis of variance had not been met, Greenhouse-Geisser adjustments of the degrees of freedom associated with the experimental and error variances, were used.

4.4 Results

4.4.1 Changes in the self-perceived (subjective) functional response as measured by IKDC

An ANOVA using factors of group (NCON; CON) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) with repeated measures on the latter factor showed that while patients in NCON and CON groups, self-perceived function improved during the follow-up period, group mean scores associated with the NCON rehabilitation conditioning were superior ($F_{(2.1, 131.6)}^{GG} = 4.5; p<0.01$). Testing of an a priori ‘difference’ hypothesis of greater progressive increases in IKDC scores (maximum score, 100) associated with the NCON versus contemporary CON rehabilitation suggested that superior function at 12 weeks post-surgery compared to previous assessments at 6 weeks post-surgery and pre-surgery, contributed most to the overall significant interaction ($69.3 \pm 10.0$ versus $49.4 \pm 8.3$ and $55.4 \pm 10.4$ compared to $63.3 \pm$
10.0 versus 48.4 ± 9.1 and 55.3 ± 10.2 for NCON and CON groups, respectively; \((F_{(1, 60)} = 29.9; \ p<0.005)\) [Figure 4.4].

The maximum relative effect associated with this comparison ([(mean score post-surgery – mean score pre-surgery)/pooled standard deviation; Cohen’s \(d\)) was a 1.92 increase in the patients’ self-perceived function for those undertaking NCON conditioning and a 1.21 increase in function for those patients receiving the standard CON rehabilitation.

In general, the group mean peak relative difference in improvement of patients’ self-perceived function associated with NCON versus standard CON conditioning was 10.8% of baseline IKDC scores. The corresponding group mean IKDC scores at 48 weeks post-surgery of patients undertaking NCON rehabilitation conditioning showed 8.5% superiority.

![Figure 4.4](image)

**Figure 4.4** IKDC measuring self-perceived changes in function following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.
4.4.2 Changes in the self-perceived (subjective) functional response as measured by KOOS

Analyses associated with KOOS (subscales: pain; sport and recreation functioning; quality of life) scores showed improvements in self-perceived knee function during the follow-up period, and that improvements were generally greater in the NCON condition ($F_{(2.2, 134.7)} > 5.5; p<0.05$). *A-priori* analyses suggested that the overall trend across the 5 sub-scales of KOOS (subscales: pain; sport and recreation functioning; quality of life) showed that superior function at 12 weeks post-surgery compared to previous assessment scores at 6 weeks post-surgery and pre-surgery in favour of the NCON group compared to the CON group contributed substantively to the overall significant group x time interaction ($F_{(2.2, 134.7)} > 5.5; p<0.05$). At 12 weeks, NCON group had showed an average 10.7 unit advantage on KOOS compared to the scores of the CON group (~10.7% advantage across the 5 subscales [maximum subscale score, 100]) and that this superiority for the NCON group was maintained to 48 weeks (~ 5.9%; $F_{(1, 60)} = 17.2; p<0.01$) [Figure 4.5].

The relative effect sizes associated with this comparison ([mean score post-surgery – mean score pre-surgery]/pooled standard deviation; Cohen’s *d*) for NCON versus CON were 0.59 and 0.36 at 12 and 48 weeks, respectively.
Figure 4.5  KOOS measuring self-perceived changes in function (all five domains individually represented) following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery (standard deviation bars omitted for graphic clarity).

4.4.3 Changes in the self-perceived (subjective) functional response as measured by PP

An ANOVA using factors of group (NCON; CON) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) with repeated measures on the latter factor showed that while patients in both experimental NCON and control CON groups self-perceived reducing physical need and discrepancies in performance between non-injured and injured legs during the follow-up period, group mean scores associated with the NCON rehabilitation conditioning were superior ($F_{(1.9, 121.4)} = 14.6; p<0.001$). Testing of an *a priori* ‘difference’ hypothesis of greater progressive increases in performance profile scores (maximum score, 10) associated with the NCON versus contemporary (CON) rehabilitation suggested that superior performance profile scores at each
assessment point up to 24 weeks post-surgery relative to antecedent scores, contributed most to the overall significant interaction (5.5 ± 1.2 versus 4.5 ± 1.6 and 4.9 ± 1.4 versus 4.7 ± 1.5 for NCON and CON groups, 24 weeks post-surgery versus pre-surgery scores, respectively; \( F_{1, 62} > 4.4; p<0.05 \)). [Figure 4.6]).

![Figure 4.6](image)

**Figure 4.6** Performance profile (PP) measuring self-perceived changes in function following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.

The maximum relative effect associated with this comparison ([mean score post-surgery – mean score pre-surgery]/pooled standard deviation) was a 0.71 increase in the patients’ self-perceived function for those undertaking NCON conditioning and a 0.13 increase in function for those patients receiving the standard CON rehabilitation. In general, the group mean peak relative difference in improvement of patients’ self-perceived function associated with NCON versus standard CON conditioning was 12.7% of baseline performance profile scores. The corresponding group mean performance profile scores at 48
weeks post-surgery of patients undertaking NCON rehabilitation conditioning showed a 6.2% advantage.

4.5 Assessor-patient interactions

4.5.1 Changes in the primary subjective outcome of function (as measured by IKDC, KOOS and PP) and the influence of assessor-patient interactions

The potential influences on self-perceived function of clinico-social approbation by patients associated with increased assessment assessor-patient interactions was analysed using separate ANOVAs involving factors of group (NCON; CON [matched assessor-patient interaction with experimental condition]; Limited testing CON [minimal assessor-patient interaction compared to experimental condition]) by test occasion (pre-surgery versus 48 weeks post-surgery) with repeated measures on the last factor.

An ANOVA with repeated measures confirmed that while patients in both experimental CON and both control NCON groups self-reported improved function during the follow-up period, group mean scores associated with the NCON rehabilitation conditioning were superior but that patterns of change within the IKDC, were not significantly different between control groups offering matched or minimised assessor-patient interaction (CON vs. Limited testing CON; pre-surgery vs. 48 weeks post-surgery), yet NCON conditioning demonstrated increased clinical effectiveness ($F_{(2.0, 82.0)} = 4.0; \ p<0.05$). Similar patterns of change were noted for KOOS and PP outcomes: There were no significant differences over time between control groups (CON vs. Limited testing CON; pre-surgery vs. 48 weeks post-surgery), but with an
increased level of clinical effectiveness was confirmed for the NCON intervention group \( (F_{1.6, 79.1})_{GG} = 4.1 \text{ to } 17.9; \ p<0.01 \). These findings indicate that clinical approbation by patients had not contributed to the outcome.

4.6 Intention to treat

Comparisons using univariate ANOVA of group mean responses for subjective outcome measures at pre-surgery amongst Lost to-follow-up \( (n=19) \), CON \( (n=22) \) and NCON \( (n=26) \) groups, respectively, were as follows:

IKDC: 55.6 ±9.0, 55.1 ±8.5 and 54.9 ±9.2 units \( (F_{(2,64)}=0.9, \ ns) \); PP: 4.3 ±1.2, 4.2 ±1.3 and 4.3 ±1.3 units; \( F_{(2,64)}=0.4, \ ns \); KOOS [Symptoms]: 59.1 ±9.7, 60.2 ±8.8 and 59.3 ±10.0 units \( (F_{(2,64)}=1.2, \ ns) \); KOOS [Pain]: 75.1 ±10.7, 74.2 ±11.2 and 75.3 ±10.6 units \( (F_{(2,64)}=0.9, \ ns) \); KOOS [Daily function]: 86.1 ±12.7, 85.2 ±11.8 and 85.8 ±11.6 units \( (F_{(2,64)}=0.8, \ ns) \); KOOS [Sport and recreation]: 53.1 ±7.7, 52.2 ±7.8 and 53.3 ±8.0 units \( (F_{(2,64)}=1.4, \ ns) \); KOOS [Quality of life]: 32.1 ±5.7, 31.7 ±5.8 and 32.3 ±6.0 units \( (F_{(2,64)}=1.1, \ ns) \).

No significant differences in self-perceived performance characteristics at baseline (pre-surgery) for the group mean scores amongst the study groups and those that were lost to follow-up. This suggests that the study data was not biased, despite the withdrawal of 19 patients.
4.7 Discussion

This chapter represents a novel comparison of concurrent (CON) versus non-concurrent (NCON) approaches to conditioning within injured and post-operative ACL populations, associated with the self-perceived functional outcome measures of IKDC, KOOS and PP.

The participants who had consented to this study had sustained an ACL-ligament rupture requiring reconstructive surgery. This population is worthy of investigation, due to the epidemiology of ACL injury and the extensive subsequent rehabilitation from surgery (6 – 9 months) (Kvist 2004, Beynnon et al. 2005, Grinsven et al. 2009, Trees et al. 2009, van Grinsven et al. 2010, Lobb et al. 2012, Manske 2012). The prevalence of ACL surgery and the longevity of the ensuing rehabilitation suggest a significant cost to the NHS (Zelle at al. 2005, Paxton at al. 2010) and susceptibility to the potentially detrimental training interference effect, brought about by concurrent rehabilitative conditioning.

give rise to this effect including over-training, over-reaching and fatigue, or changes in catabolic state, fibre size and recruitment patterns, for example (Docherty and Sporer 2000, Wilson et al. 2012). However, no consensus exists regarding the interference effect and what might be driving it. The literature investigating the effects of concurrent and non-concurrent training might be criticised, due to the lack of matching volume and intensity of the training across the investigated groups. Of these previous studies in asymptomatic individuals, Volpe et al. (1993) was the only study identified to match training intensity and volume. Yet, this disparity in experimental design was similar across the literature both supporting and opposing the concept of an interference effect. The majority of the studies do suggest the possibility of an interference effect when training for muscular strength and cardio-vascular endurance in close proximity, leading to attenuation of strength gains (Hickson 1980, Dudley et al. 1985, Hunter et al. 1987, Sale et al. 1990, Nelson et al. 1990, Bell 1991, Hennessy and Watson 1994, Kraemer et al. 1995, Bell et al. 2000, Doherty and Sporer 2000, Häkkinen et al. 2003, Santtila et al. 2009, Cadore et al. 2010, Karavirta et al. 2011, Wilson et al. 2012). Unlike all the previous studies (with the exception of Volpe et al. 1993), the rehabilitative conditioning was matched for intensity and volume in this research study across the experimental (NCON) and both control (CON and Limited testing CON) groups.

In order to test the effects of this novel formulation of NCON rehabilitation following ACL-reconstruction, assessments of self-perceived IKDC, KOOS and the PP scores and technique were administered. All of these measures have been used in past research when investigating the dynamic stability of the knee (Doyle et al. 1998, Fitzgerald et al. 2001, Hewitt et al. 2006, Ardern et al. 2011a, Ardern 2011b).
The duration of the study allowed for these measures to be recorded prior to the surgery in order to establish a baseline and continued throughout the 6 month period of formal rehabilitation, and then continued up to twelve months post-surgery. The latter six months addressed the period when the participants would have returned to their full function with no clinical restraints dictating their activities, effectively offering an assessment of self-managed care by the patient.

This chapter assessed the changes in self-perceived function following ACL reconstructive surgery over a 24 weeks formal rehabilitative period and up to 48 weeks post-operatively. The results show beneficial gains for all the participants, irrespective of the group to which they had been allocated randomly.

However, the specific aim of the RCT presented in this chapter was to assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on self-perceived outcome measures of function (IKDC, KOOS, PP) in patients with anterior cruciate ligament deficiency. The influence of NCON during the post-surgical, one-year follow-up appears to be positive and improves on standard practice. The study’s findings showed significant group (NCON; CON) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) and condition by test occasion interactions for the primary outcomes of function (IKDC) together with secondary outcomes of KOOS and PP (p<0.01) and confirmed increased clinical effectiveness of NCON conditioning. In general, this novel intervention offered improvements in patient-reported measures of function of between ~10.6% and 12.7% better than control at 12 and 24 weeks after surgery.
The maximum relative effect sizes associated with NCON versus CON rehabilitation in the self-perceived outcome of function scores across the 5 assessment occasions were IKDC, 1.9 and 1.2; KOOS, 0.59 and 0.36; PP, 0.71 and 0.13, respectively ($p<0.05$). It is plausible that the patterns of relative effect size for the changes in performance over the period of follow-up by patients will have been influenced by the extent of absolute changes over time for the various outcome measures used in this study, as well as by heterogeneity of conditioning dose-responsiveness. For example, relatively large percentage advantages associated with NCON compared to CON rehabilitation, might by accompanied by low relative effect size over time where there has been less consistency of response by patients to the dose of conditioning (i.e. relatively lower group standard deviation). However, these effect sizes are similar to those previously reported ($0.76 – 2.11$) in clinical populations by Irrgang et al. (2012).

Importantly, it could be speculated that the reason for the greatest changes during the acute phase of rehabilitation demonstrated by IKDC and KOOS was due to the fact that population studied were not professional athletes and most returned to their full time employment between 6 and 12 weeks post-surgery. Thus, this would confer less time might have been otherwise dedicated to rehabilitative exercises outside that of the physiotherapy out-patient session and compared to the acute post-operative period. It is plausible also that recovery from deconditioning naturally shows a rapid improvement (dose-responsiveness) and then the effect tapers off as near normal parameters are met. In addition, it might be that from 12 weeks, patient compliance to rehabilitation lessens, especially under conditions that mimic self-managed care. However, this finding is in contrast with previous
studies investigating ACL populations, where the greatest effect size is found at 6 months post-surgery (Risberg et al. 1999, Collins et al. 2011). Unfortunately, neither Risberg et al. (1999) nor Collins et al. (2011) document the ACL rehabilitative programme that had been followed. Thus, it could be speculated that the time difference in latencies for the most significant interaction might be due to the rehabilitation prescribed.

Additionally, these relatively early gains in self-perceived performance might be associated with the stage of the graft healing, providing improvements in the passive knee stability without the inhibition of the immediate post-surgical insult (Fu et al. 1999, Hopkins and Ingersoll 2000, Rice and McNair 2010, Krogsgaard et al. 2011, Oryan et al. 2013). Or conversely, the perceived improvements might be aligned to improvements in the dynamic stability of the knee. It is plausible that speedier gains in musculoskeletal and neuromuscular performance are generated by NCON training, thus providing better self-perceived (subjective) satisfaction.

By comparison, the greatest significant interaction associated with PP was found at the 24 weeks assessment occasion. By design, the PP is less restrictive than either the IKDC and KOOS, items scored were bespoke to the individual patient’s needs. Therefore, it might be that these areas of concern required more time to improve. The patient might have associated these constructs with long term gains in function. No restrictions were placed on patients from 6 months post-ACL surgery and it might be that the PP reflected this.

In summary, compared to CON, there were consistent statistically significant gains in subjective function associated with NCON conditioning rehabilitation. For example, in the NCON group, the significant group
improvement of 8.5% in IKDC scores at 48 weeks post-surgery might reflect important gains in self-perceived patient satisfaction, which in turn, might improve compliance in the rehabilitation, and thus in a cascade of change, aid improvements in the self-perceived outcome measures.

Finally, the assessor-patient interaction is a potential factor that should not be ignored when examining populations in a clinical environment. In order to address this issue the study also aimed to investigate the possibility of clinical and/ or social approbation brought about by increased assessor-patient interaction. The consistent findings amongst the study’s outcomes of statistical similarity of interaction responses over time both control groups (CON and Limited testing CON [minimal interaction]) suggest minimal intrusion from clinical approbation. These findings also offer a ‘manipulation-check’ that group mean responses properly reflect the effects of non-concurrent conditioning in this clinical population.

4.8 Conclusion

There appears to be consistent evidence from this study to endorse the self-perceived advantages of NCON rehabilitation conditioning compared to current CON practice. Thus, the null-hypothesis relating to this chapter and associated with primary aim for the thesis of *similar self-perceived (subjective) functional gains measured using IKDC, KOOS, PP, will be accomplished by rehabilitating from ACL surgery over time in a NCON format compared to the traditional phasing of concurrent (CON) conditioning*, can be rejected. Both traditional CON and NCON rehabilitation following ACL surgery are beneficial in restoring the subjective measures associated with ACL reconstruction and rehabilitation. Nonetheless, separating cardio-vascular endurance exercise
from heavy resistance muscular exercise (NCON) is more advantageous to recovery, particularly in the acute phases of recovery. Speculatively, this is when the graft tissue is in the early stages of remodelling and might be at a greater risk of damage through detrimental dosage of physical activity. The overall improvement from this altered sequencing of rehabilitation prescription centres around ~12% for all subjective measures. Although, this amount of improvement implies clinical significance for self-perceived measures (Collins et al. 2011, Irrgang et al. 2012), it does not account for whether there might be corresponding changes in objective measures of function and performance. While this increased level of self-perceived function generated by NCON rehabilitation might suggest that a speedier or safer return to sport is possible, it does not identify if objective measurements are beneficially affected. Therefore, the premise of understanding when it might be safe to return to sport and full functional capabilities has not been completely answered in this section.

Consequently, the following chapter investigates the effects of NCON conditioning following ACL reconstructive surgery on objective measures relating to function (hop for distance [HOP]), and in addition to musculoskeletal and neuromuscular performance.
Chapter 5:
Effects of Anterior Cruciate Ligament Reconstruction Surgery and Non-Concurrent Strength and Endurance Rehabilitation on Objective Functional, Musculoskeletal and Neuromuscular Performance
Chapter abstract

Title: Effects of anterior cruciate reconstruction surgery and non-concurrent strength and endurance rehabilitation on objective functional, musculoskeletal and neuromuscular performance: A prospective, random-allocation controlled study.

Context: Rupture of ACL is both common and serious. It is associated with a high economic and social cost to the individual and society. Anterior cruciate ligament surgery takes a minimum of 6 months rehabilitation. Nevertheless, judging the timing for safe return to sport is currently speculative. Evidence exists in healthy populations to suggest greater strength gains can be achieved by training non-concurrently. As ACL rehabilitation is traditionally performed concurrently, there is potential for additional gains in the extent of improvements in function, musculoskeletal and neuromuscular performance by manipulating resistance and cardio-vascular exercise into a non-concurrent sequence during post-surgical rehabilitation. As these factors are associated with injury prevention and/ or dynamic stability of the knee, it might contribute to a speedier or safer return to function. Objective: The purpose of this randomised control trial was to assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on objective measures of functional capability and of musculoskeletal and neuromuscular performance associated with anterior cruciate deficient knees (primary outcome of function [HOP]; secondary outcomes of musculoskeletal and neuromuscular performance [ATFD, PF, EMD, RFD, SMP]). Setting: Orthopaedic Hospital NHS Foundation Trust. Design: Prospective random-allocation to group trial involving iso-volume rehabilitative
intervention versus contemporary practice, using contralateral limb assessment and clinico-social approbation controls. The design compared the effects of experimental post-surgical rehabilitation comprising non-concurrent strength and endurance conditioning with two conditions of control reflecting contemporary clinical practice (matched versus minimal assessment interaction). **Participants:** Eighty two patients (69♂, 13♀, age: 35.4 ± 8.6 yr; time from injury to surgery 9.4 ± 6.9 months [mean ± SD]) electing to undergo unilateral ACL reconstructive surgery (semitendinosus and gracilis graft [n = 57]; central third, bone-patella tendon-bone graft [n = 25]); were allocated to groups (2:2:1 purposive sampling ratio, respectively). Nineteen patients had been lost to follow-up. **Intervention:** A patient group following a standardised traditional concurrent (CON) ACL rehabilitation programme acted as the control versus a group following an experimental non-concurrent (NCON) ACL rehabilitation programme that involved separation of strength and cardiovascular endurance conditioning. An additional control group (Limited testing CON) matched the CON group rehabilitation applied within contemporary clinical practice. **Outcome Measures:** The primary objective outcome was an index of function, HOP; secondary outcomes (ATFD, PF, RFD, EMD and SMP) objectively assessed musculoskeletal and neuromuscular performance associated with the knee extensors and flexors of the injured and non-injured legs. These objective outcomes were assessed on five separate occasions (pre-surgery, and at 6, 12, 24 and 48 weeks post-surgery). However, assessment occasions were purposefully reduced to pre-operative and at 48 weeks post-operative only for the Limited testing CON group. **Results:** Factorial analyses of variance (ANOVAs) with repeated-measures showed significant group (NCON; CON) by leg (injured/non-injured) by test occasion
(pre-surgery, 6, 12, 24 and 48 weeks post-surgery) interactions for primary outcome of function (HOP) together with secondary outcomes of ATFD, PF, RFD, EMD and SMP for the knee extensor musculature. Similar responses were noted for the knee flexors of the injured and non-injured legs ($F_{(2,124)} \ GG = 4.5$ to $6.6; \ p<0.01$) and confirmed increased clinical effectiveness of non-concurrent conditioning (range $\sim 4.7\%$ - $15.3\% \ (10.8\%)$ compared to control between 12 and 48 weeks). Patterns of improvements in physical fitness capabilities for the NCON group over time were represented by a relative effect size range of 1.92 to 2.89. Improvement patterns were not significantly different between control groups offering matched or minimised assessor-patient interaction (CON vs. Limited testing CON; pre-surgery versus 48 weeks post-surgery) indicating that clinical approbation by patients had not contributed to the outcome. **Conclusion:** Overall, the patterning and extent of changes amongst objective functional and musculoskeletal and neuromuscular performance scores offer support for the efficacy of using NCON strength and endurance conditioning to enhance post-surgery rehabilitation.
5.2 Introduction


One of the first studies to investigate this topic was presented by Hickson (1980), comparing the strength performance and aerobic power in three groups, conditioning separately for strength, endurance and a combination of strength and endurance, respectively over a 10 week period. The findings showed no difference in maximum oxygen uptake (VO$_{2}$max) for the endurance and concurrent group. However, there was a decline in strength gain at the 9 - 10 week stage in the concurrent group compared to that of the purely strength-training group. Hickson (1980), concluded that there is little or no benefit for endurance athletes to train for strength at the same time and that it could be deleterious for strength athletes to perform high-level endurance activities while simultaneously training for strength.

reason why the nature of responses to combined strength and endurance training are thought to be divergent from what might otherwise be expected from training for strength and endurance separately, is the subject of speculation. However, the possible concept of an 'interference effect' has been proposed with varying suggestions as to why this might occur, ranging from overtraining, alterations in recruitment patterns and fibre type to adaptations in myoglobin content, oxidative enzymes, muscle capilliarisation, mitochondrial volume and activity. Unfortunately, no agreed consensus exists (Gravelle et al. 2000, Docherty and Sporer 2000, Wilson et al. 2012).

Previous trials have been criticised for the inconsistency of exercise volume and intensity across study groups (Wilson et al. 2012). However, this disparity cannot be the sole reason for the effects of incompatibility, as this was also the case in the studies which found no attenuation in strength following concurrent conditioning (McCarthy et al. 1995, Gravelle et al 2000, McCarthy et al. 2002, Balabinis et al. 2003, Leveritt et al. 2003, Kraemer 2004 Glowacki et al. 2004).

Upon completion of the review of the literature for this thesis, no study was found to have investigated the effect of non-concurrent training on injured or post-operative populations. As strength improvement is a key objective for rehabilitation, the notion that non-concurrent sequencing of rehabilitative exercise might produce better improvements is of great clinical interest.

As previously discussed, ACL injury is both common and serious, and the ramifications are costly to the individual and society (Zelle et al. 2005, Louw et al. 2008, Paxton et al. 2012). A minimum of 6 months post-operative rehabilitation is required following surgical reconstruction (van Grinsven et al. 2010, Lobb et al. 2012, Manske et al. 2012). Therefore, there is a potential for
attenuation of strength gains during this period of rehabilitation brought about by the contemporary rehabilitative practice of concurrent conditioning.

In addition to limiting deconditioning and improving strength following ACL surgery, training to enhance neuromuscular performance plays a key role in rehabilitation programmes. Indeed programmes focusing on neuromuscular conditioning, have been shown to lessen the incidence of ACL injury (Griffin et al. 2005, Hewitt et al. 2006). Therefore, when considering objective outcome measures suitable for ACL populations, both musculoskeletal and neuromuscular parameters are valuable. The musculoskeletal and neuromuscular dimensions that have been tentatively linked with dynamic stability of the knee and ACL injury and prevention are anterior tibio-femoral displacement (ATFD), peak force (PF), rate of force development (RFD), electromechanical delay (EMD) and sensorimotor performance (SMP) (Caraffa et al. 1996, Borsa et al. 1998, Risberg 1999, Fitzgerald et al. 2001, Hopper et al. 2002, Hewitt et al. 2006, Harreld et al. 2006, Griffin et al. 2006, Minshull et al. 2011, Renstrom et al. 2008, Gleeson et al. 2008a, Gleeson et al. 2008b, Minshull et al. 2009, Ardern et al. 2010, Thomee et al. 2011, Minshull et al. 2011, Sugimoto et al. 2012). Therefore, in order to establish the outcome of recovery following ACL surgery, it would be advisable to measure these indices.

Chapter 4 investigated the influence of both the traditional concurrent (CON) rehabilitation and a manipulated pattern of non-concurrent (NCON) rehabilitation or self-perceived outcomes following ACL surgery over a 48 weeks post-operative period. However, in contrast, the following chapter investigates the effects of NCON conditioning by assessing objective outcomes and using the same population and experimental intervention.
The purpose of the randomised control trial presented in this chapter was to assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on objective measures of functional capability and of musculoskeletal and neuromuscular performance associated with anterior cruciate deficient knees
(primary outcome of function [HOP]; secondary outcomes of musculoskeletal and neuromuscular performance [ATFD, PF, EMD, RFD, SMP]). In addition, the possibility of clinico-social approbation brought about by increased assessor-patient interaction was examined.

It was hypothesised that significantly enhanced objective functional, musculoskeletal and neuromuscular gains as measured by HOP, ATFD, PF, RFD, EMD and SMP, will be accomplished by rehabilitating from ACL surgery over time in a NCON format compared to the traditional phasing of concurrent (CON) conditioning.

Therefore, the following chapter describes a prospectively randomised control trial, investigating the effects of reconstruction surgery and non-concurrent strength and endurance (NCON) rehabilitation on objectively-measured functional, musculoskeletal and neuromuscular outcomes in patients with anterior cruciate ligament-deficiency.
5.3 Methods summary

The detailed descriptions of apparatus and procedures for the assessment of outcomes that have been used in this study can be found in Chapter 3 – General Methods. Documented below is a methodological summary to briefly outline the participants, experimental design, and approaches to the statistical testing of hypotheses used in this RCT.

5.3.1 Participants

Eighty two patients electing to undergo unilateral ACL-reconstructive surgery (central third, bone-patella tendon-bone graft \(n = 25\), or semitendinosus and gracilis graft \(n = 57\)) at a U.K. National Health Service Foundation Trust hospital gave their informed consent to participate in the study. Patients were treated by two consultant orthopaedic surgeons (DR; SR) of similar experience and practice. Upon meeting the inclusion exclusion criteria (Chapter 3 – Section 3.2.2), the patients were randomised into one of three groups. Table 5.1 summarises the allocation and characteristics of the populations in each study group.

<table>
<thead>
<tr>
<th>Study Group</th>
<th>Male (n)</th>
<th>Female (n)</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Body Mass (kg)</th>
<th>Time from injury to surgery (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CON</td>
<td>29</td>
<td>2</td>
<td>37.7 ± 8.8</td>
<td>1.77 ± 0.07</td>
<td>81.4 ± 12.3</td>
<td>9.4 ± 6.9</td>
</tr>
<tr>
<td>NCON</td>
<td>27</td>
<td>6</td>
<td>36.6 ± 9.0</td>
<td>1.76 ± 0.09</td>
<td>82.4 ± 11.1</td>
<td>8.3 ± 6.7</td>
</tr>
<tr>
<td>Limited testing CON</td>
<td>13</td>
<td>5</td>
<td>34.2 ± 8.1</td>
<td>1.79 ± 0.09</td>
<td>81.1 ± 17.3</td>
<td>9.1 ± 7.2</td>
</tr>
</tbody>
</table>

Table 5.1 Allocation and characteristics for patients associated with each of the three study groups CON, NCON and Limited testing CON.
5.3.2 Ethical approval

This study met the ethical standards suggested by Harriss and Atkinson (2009), and the study was approved by the Ethics Committee for Human Testing of the University of Exeter, UK, and by the Shropshire area NHS Ethics Committee (REC reference 05/Q2601/36) and had received scientific merit approval from the Research Committee of Orthopaedic NHS Foundation Trust, UK. The study can be tracked using the reference code R5613 with respect to The National Institute for Health Research (NIHR) Clinical Research Network (CRN).

5.3.3 Randomisation

Patients were prospectively randomised to one of three groups:

**CON** (n=31; n=9 lost to follow-up) comprising a standardised and established programme of exercise rehabilitation used in current clinical practice (24 weeks of structured and supervised rehabilitation conditioning).

**NCON** (n=33; n=7 lost to follow-up) comprising and matching the type, volume and intensity associated with the programme of exercise rehabilitation prescribed in CON, but modified to include the novel and specific phasing of strength and endurance exercises and designed to minimise physiological inhibition associated with concurrent strength and endurance conditioning.

**Limited testing CON** (n=18; n=3 lost to follow-up) matching the programme of exercise rehabilitation used in CON but with purposefully minimised attention and assessor-patient interaction during rehabilitation outcome assessments, other than those during assessments and recruitment to the study (pre-surgery) and at its completion (48 weeks post-surgery).
5.3.4 Batch Allocation

Patients were sequentially batch-allocated in a randomised-fashion to groups (CON; NCON; Limited testing CON) using a purposive sampling ratio (2:2:1), respectively. This enabled optimisation of experimental design sensitivity amongst comparisons associated with the two primary ‘arms’ of the study (CON and NCON versus Limited testing CON).

5.3.5 Intention to treat

Patients lost to follow-up affected varying assessment sessions [Figure 5.1]. No secondary injuries occurred to any of the patients during the rehabilitation or assessment process. Therefore, secondary injury was not a contributing factor in lost to follow-up. However, as stated in the patient information (see Appendix E), patients who were lost to follow-up were not questioned as to why they chose to leave the study at a particular point, although 10 of the 19 patients did voluntarily offer the reason of work/ life commitments intruding on the time available to contribute to the research study.

The potential influences of bias on this study’s findings associated with altered group composition and altered patterns of outcome data due to patients being lost to follow-up was assessed using separate ANOVAs for the baseline (pre-surgery) scores each outcome measure involving factors of group (NCON; CON; Limited CON; Lost to-follow-up) by leg (injured; non-injured) with repeated measures on the last factor. The lost to-follow-up results are presented in section 5.6. All the outcomes were assessed at baseline. All the outcomes showed statistically similar characteristics at baseline amongst the group mean scores for experimental groupings and for those patients who had
been lost to follow-up. This suggested cautiously, that biasing of data might have intruded in only a minor way in this study.
Figure 5.1 Consort Diagram – summary of the number of patients recruited, the random allocation and those lost to follow-up associated with objective measures function, musculoskeletal and neuromuscular performance following either CON or NCON ACL rehabilitation.
5.3.6 Intervention

A full and detailed description of the post-operative ACL rehabilitation followed by each group (CON, NCON and Limited testing CON) is found in Chapter 3 – Section 3.3.

In summary, all the groups followed the same rehabilitative guide [Appendix A - RJAH anterior cruciate ligament rehabilitation guide] with respect to the progression of activity and function. This is largely dictated by the healing process of the graft tissue. On average, it takes approximately 6 weeks to overcome the insult of the surgery with respect to activity and function. During this acute phase, rehabilitative exercises are progressed as the patients symptoms allow. For up to 3 months following surgery, physical restrictions are placed on performing open kinetic chain quadriceps exercises, running and twisting and turning on the knee. However, from this point, the restrictions no longer apply, with the exception of predictable twisting and turning type manoeuvres at speed, which was not formally introduced until 4 months after surgery, progressing to unrestricted agility from 5 months post-surgery. It is not until 6 months following ACL reconstruction that no physical restrictions are placed on the patients and full-contact sports are gradually introduced. However, traditionally ACL rehabilitation includes both heavy resistance exercises and cardio-vascular endurance exercises to be performed within the same treatment session (CON). The study intervention sequentially separated these exercises to different days (NCON). The intensity and volume across the groups was standardised over each month. In addition, to the clinical notes documenting each supervised rehabilitation session, patients also recorded their self-administered activity by means of a diary.
5.3.7 Experimental and assessment procedures

Patients were assessed on five separate occasions (pre-surgery, and at 6, 12, 24 and 48 weeks post-surgery) with the exception on Limited testing CON (pre-surgery and 48 weeks post-surgery). After surgery, all patients were treated and assessed by the same physiotherapist for the duration of their rehabilitation period.

The first assessment session included time for patients to become familiarised with the experimental and assessment procedures and protocols, and was devised to obtain baseline pre-surgery measures. During the initial meeting with the assessor (~2 weeks prior to surgery) and at subsequent assessment sessions (conducted at 6 weeks, 12 weeks, 24 and 48 weeks) following surgery, each patient was assessed for primary objective outcome of function HOP together with secondary outcomes of musculoskeletal and neuromuscular performance. The latter included ATFD, PF, RFD, EMD and SMP associated with the knee extensors and flexors of the injured and non-injured legs.

Assessments of outcomes and the order of testing legs were undertaken in a random sequence.

Prior to all testing, patients undertook a standardised warm-up protocol described in Chapter 3 – Section 3.4.

5.3.7.1 Functional performance measure

Following two to three practice attempts, the patient hopped as far as possible starting on one leg and landing on the same leg (HOP). The distance was measured and the mean of 3 inter-trial replicates subsequently used for analysis (Chapter 3 – Section 3.7.1).
5.3.7.2 Musculoskeletal performance measure

Assessment of anterior tibio-femoral displacement (ATFD) was measured using a previously described method (Chapter 3 – Section 3.8.1).

5.3.7.3 Neuromuscular performance measures

A mean of 3 maximal volitional muscle activation was calculated for both the knee extensors and flexors in the injured and non-injured limbs as a measure of peak force. The instructional methodology is detailed in Chapter 3 – Section 3.8.2.

Electromyographic activity (EMG) was recorded and described in Chapter 3 – Section 3.8.3.

The rate of force development (RFD) was calculated as the average rate of force increase between 25% and 75% of PF (Chapter 3 – General Methods – Section 3.8.3).

Electromechanical delay (EMD) was computed as the time lag between the onset of muscle activity and the onset of force using the mean of 3 intra-trial muscle activations (Chapter 3 – Section 3.8.3).

Sensorimotor performance (SMP) was measured by the force error (FE) arising from a task that required the ‘blinded’ replication using the knee flexors of a target force (50 % of pre-operative of PF) (Chapter 3 – Section 3.8.4).

5.3.8. Statistical analyses

The clinical efficacy of non-concurrent conditioning was assessed using separate analyses of variance (ANOVAs) for the objectively-measured outcome of function (HOP) and the musculoskeletal and neuromuscular performance associated with the secondary outcomes of ATFD, PF, RFD, EMD and SMP.
The ANOVA model involving factors of group (NCON; CON) by leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) with repeated measures on the latter two factors was used to test the null-hypothesis of *similar objective functional, musculoskeletal and neuromuscular gains as measured by HOP, ATFD, PF, RFD, EMD and SMP, will be accomplished by rehabilitating from ACL surgery over time in a NCON format compared to the traditional phasing of concurrent (CON) conditioning.*

The outcome performances associated with the knee extensors and flexors of both injured and non-injured legs were assessed separately, where appropriate.

The potential influences on objective function and musculoskeletal and neuromuscular performance of clinico-social approbation by patients associated with increased assessment assessor-patient interactions was assessed using separate ANOVAs involving factors of group (NCON; CON [matched assessor-patient interaction with experimental condition]; Limited testing CON [minimal assessor-patient interaction compared to experimental condition]) by test occasion (pre-surgery versus 48 weeks post-surgery) with repeated measures on the last factor.

*A priori* alpha levels were set at *p*<0.05. The experimental design offered an approximate 0.70 power of avoiding a Type-II error when employing a least detectable difference of 0.2 mm, 16N, 40N·s⁻¹, 4ms, 2.5%, during comparisons of ATFD, PF, RFD, EMD, and SMP, scores over time, respectively (Lipsey 1990). Where selected assumptions underpinning analysis of variance had not been met, Greenhouse-Geisser adjustments of the degrees of freedom associated with the experimental and error variances were used.
5.4 Results

5.4.1 Changes to the objectively-measured primary outcome of function

5.4.1.1 Function - Hop for distance (HOP)

Analysis of variance with repeated measures showed significant group (NCON; CON) by leg (injured/non-injured) by test occasion (pre-surgery, 12, 24 and 48 weeks post-surgery) interaction for HOP (injured leg outcome at 6 weeks post-surgery were not acquired on cautionary clinical advice and corresponding data was not available for analyses). Group mean scores for HOP suggested that while patients in both NCON and CON groups showed improved performance during the follow-up period, group mean scores associated with the NCON rehabilitation conditioning confirmed superior capability for both legs but that this was more pronounced in the injured leg ($F_{(2.1, 133.0)}^{GG} = 4.2; p<0.01$).

A priori ‘difference’ testing of greater progressive increases in HOP scores associated with the NCON versus contemporary CON rehabilitation suggested that superior performance for the injured leg at 12 weeks post-surgery compared to pre-surgery, contributed most to the overall significant interaction (103.7 ± 21.8 cm versus 96.1 ± 25.1 cm [i.e. gain in performance] and 91.8 ± 21.8 cm versus 99.1 ± 24.2 cm [i.e. loss in performance] for the injured leg of patients in NCON and CON groups, respectively; $F_{(1, 62)} = 13.1; p<0.005$), [Figure 5.2].
The maximum relative effect associated with this comparison during the acute phase of rehabilitation ([mean score post-surgery – mean score pre-surgery]/pooled standard deviation) was a 0.34 increase in the patients’ injured leg HOP performance for those undertaking NCON conditioning and a 0.32 decrease in performance for those patients receiving the standard (CON) rehabilitation.

In general, the group mean peak relative difference in improvement of patients’ objectively-measured function associated with NCON versus standard (CON) conditioning at 12 weeks post-surgery was 12.2% of baseline single-leg hop scores. The corresponding group mean injured leg HOP scores at 48 weeks post-surgery of patients undertaking NCON rehabilitation conditioning showed a 6.3% advantage.

Figure 5.2 Single leg hop [HOP] for distance for both the injured and non-injured limbs changes following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.
5.4.2 Changes to the objectively-measured secondary outcomes of musculoskeletal and neuromuscular performance

5.4.2.1 Musculoskeletal performance - anterior tibio-femoral displacement (ATFD)

Analysis of variance with repeated measures showed significant group (NCON; CON) by leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) interaction for anterior tibio-femoral displacement (ATFD). Group mean scores for ATFD suggested that while patients in both experimental NCON and CON groups showed improved laxity during the follow-up period, NCON rehabilitation conditioning provoked improved laxity for both injured and non-injured knees but that this was more pronounced in the injured leg (F\textsubscript{(1.3, 79.8)} = 14.9; p<0.005).

A priori ‘difference’ testing of hypotheses for greater progressive decreases in anterior tibio-femoral displacement scores associated with the NCON versus contemporary CON rehabilitation suggested that superior rates of re-establishing ATFD in the injured knee to be approximately the same as that of the non-injured contralateral control leg from pre-surgery to 48 weeks of rehabilitation post-surgery, contributed most to the overall significant interaction (4.5 ± 0.8 mm versus 15.4 ± 2.7 mm and 4.6 ± 0.9 mm versus 13.3 ± 2.9 mm [48 weeks post-surgery versus pre-surgery], for the injured leg of patients in NCON and CON groups, respectively; F\textsubscript{(1, 62)} > 7.1; p<0.005), [Figure 5.3]).
The overall relative effect associated with this comparison during the acute phase of rehabilitation ([mean score post-surgery – mean score pre-surgery]/pooled standard deviation) was a 6.0 increase in the patients’ injured leg ATFD performance (i.e. a reduced ATFD) for those undertaking NCON conditioning and a 4.8 increase in performance for those patients receiving the standard CON rehabilitation.

In general, the group mean peak relative difference in improvement of patients’ knee laxity associated with NCON versus standard CON conditioning was 14.2% of baseline injured leg ATFD scores.
5.4.2.2 Neuromuscular performance - peak force (PF)

Factorial analysis of variance with repeated measures showed significant leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) \( (F_{(1.6, 99.6)}^{GG} = 89.8; \ p<0.005) \) and group (NCON; CON) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) \( (F_{(1.4, 84.8)}^{GG} = 4.0; \ p<0.05) \) interactions for peak force elicited from the knee extensor musculature. The absence of an interaction between all three factors suggested that while patterns of improvement in strength over time were separately dependent on which leg was being assessed and under which regime of rehabilitation conditioning had taken place, the strength performance of injured and non-injured legs had not been differentially influenced by NCON conditioning.

Of most interest to this study, a priori ‘difference’ testing of hypotheses for greater progressive increases in peak force scores associated with the NCON versus contemporary (CON) rehabilitation suggested that superior rates of either maintaining or re-establishing strength capability in the knee extensor musculature of both legs from pre-surgery to 6 weeks post-surgery (for example, 325 ± 78 N versus 372 ± 127 N and 298 ± 64 N versus 374 ± 68 N [6 weeks post-surgery versus pre-surgery], for the injured leg of patients in NCON and CON groups, respectively; \( F_{(1, 62)} = 5.8; \ p<0.05 \)) and from pre-surgery to 24 weeks post-surgery (382 ± 93 N versus 372 ± 127 N and 350 ± 77 N versus 374 ± 68 N [24 weeks post-surgery versus pre-surgery], for the injured leg of patients in NCON and CON groups, respectively; \( F_{(1, 62)} = 9.3; \ p<0.005 \)), contributed most to the overall significant interaction, [Figure 5.4]).

Equivalent biostatistical testing of hypotheses assessing the effects of NCON rehabilitation conditioning on strength performance in the knee flexor musculature showed similar patterns of response including significant leg by
test occasion \( F(2.4, 147.4)_{GG} = 58.4; p<0.005 \) and group by test occasion \( F(2.5, 152.3)_{GG} = 5.8; p<0.005 \) interactions [Figure 5.5].

Non-concurrent (NCON) conditioning appeared to have been most influential for enhanced maintenance or re-establishment of strength in the knee flexors in the periods of rehabilitation from pre-surgery to 6 weeks post-surgery (185 ± 47 N versus 216 ± 83 N [15.0% loss of strength compared to baseline] and 157 ± 63 N versus 209 ± 65 N [24.1% loss of strength compared to baseline] 6 weeks post-surgery versus pre-surgery, for the injured leg of patients in CON groups, respectively; \( F(1, 62) = 6.1; p<0.05 \) and from pre-surgery to 12 weeks post-surgery (224 ± 54 N versus 216 ± 83 N [3.7% gain in strength compared to baseline] and 190 ± 48 N versus 209 ± 65 N [10.1% loss of strength compared to baseline] 12 weeks post-surgery versus pre-surgery, for the injured leg of patients in CON groups, respectively; \( F(1, 62) = 13.1; p<0.001 \)).

The peak effects associated with this comparison during the acute phase of rehabilitation ([mean score post-surgery – mean score pre-surgery]/pooled standard deviation) was a 0.5 loss to 0.1 gain in the patients’ injured leg’s peak force performance (knee extensors and flexors) for those undertaking NCON conditioning and a 0.8 to 0.3 loss in performance for those patients receiving the standard (CON) rehabilitation.

In general, the group mean peak relative difference in improvement of patients’ knee strength associated with NCON versus standard (CON) conditioning at 48 weeks post-surgery was 9% and 6% of baseline non-injured leg’s peak force scores during knee extension and flexion, respectively.
Figure 5.4  Measurement of peak force of the knee extensors [PF] (N) of the injured and non-injured knees, following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.

Figure 5.5  Measurement of peak force of the knee flexors [PF] (N) of the injured and non-injured knees, following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.
5.4.2.3 Neuromuscular performance - rate of force development (RFD)

Factorial analysis of variance with repeated measures showed significant leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) ($F_{(1.6, 96.9)}^{GG} = 48.9; p<0.005$) and group (NCON; CON) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) ($F_{(1.6, 97.5)}^{GG} = 3.5; p<0.05$) interactions for RFD scores elicited from the knee extensor musculature. The findings suggested that patterns of improvement in RFD over time were different for injured and non-injured legs and that NCON conditioning offered enhanced patterns of recovery for knee extensor RFD performance.

A priori ‘difference’ testing of hypotheses for greater progressive increases in RFD scores associated with the NCON versus contemporary CON rehabilitation suggested that superior rates of either maintaining or re-establishing RFD capability in the knee extensor musculature of both legs from pre-surgery to 12 weeks post-surgery (for example, $3800 \pm 1330$ N·s$^{-1}$ versus $2880 \pm 1230$ N·s$^{-1}$ and $3400 \pm 1060$ N·s$^{-1}$ versus $2820 \pm 1070$ N·s$^{-1}$ [12 weeks post-surgery versus pre-surgery] for the injured leg of patients in the NCON and CON groups, respectively; and $3850 \pm 1380$ N·s$^{-1}$ versus $4130 \pm 1520$ N·s$^{-1}$ [i.e. less de-conditioning] and $3690 \pm 1080$ N·s$^{-1}$ versus $4210 \pm 1240$ N·s$^{-1}$ for the non-injured leg of patients in the NCON and CON groups, respectively; $F_{(1, 62)} = 15.7; p<0.005$) contributed most to the overall significant interaction, [Figure 5.6].
Figure 5.6  Measurement of rate of force of the knee extensors development (N·s⁻¹) over time of the injured and non-injured knees, following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.

Figure 5.7  Measurement of rate of force of the knee flexors development (N·s⁻¹) over time of the injured and non-injured knees, following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.
Equivalent biostatistical testing of hypotheses assessing the effects of NCON strength and endurance rehabilitation conditioning on strength performance in the knee flexor musculature showed similar patterns of response including significant leg by test occasion \( F_{(1.8, 110.1)}^{G_G} = 34.4; p < 0.005 \) and group by test occasion \( F_{(1.7, 106.5)}^{G_G} = 5.7; p < 0.005 \) interactions [Figure 5.7]. NCON conditioning appeared to have been most influential for enhanced maintenance or re-establishment of RFD in the knee flexors in the periods of rehabilitation from pre-surgery to 12 weeks post-surgery (for example, 2660 ± 890 N·s\(^{-1}\) versus 2200 ± 790 N·s\(^{-1}\) and 2110 ± 720 N·s\(^{-1}\) versus 2060 ± 900 N·s\(^{-1}\) [12 weeks post-surgery versus pre-surgery], for the injured leg of patients in the NCON and CON groups, respectively; and 2560 ± 880 N·s\(^{-1}\) versus 2600 ± 910 N·s\(^{-1}\) [i.e. less de-conditioning] and 2200 ± 680 N·s\(^{-1}\) versus 2460 ± 760 N·s\(^{-1}\) for the non-injured leg of patients in the NCON and CON groups, respectively; \( F_{(1, 62)} = 28.4; p < 0.005 \)).

The peak effects associated with this comparison during the acute phase (pre- to 12 weeks post-surgery) of rehabilitation ([mean score post-surgery – mean score pre-surgery]/pooled standard deviation) were 0.71 and 0.54 gains (knee extension and flexion, respectively) in the patients’ injured leg’s rate of RFD performance for those undertaking NCON conditioning and a 0.56 gain to 0.04 loss (knee extension and flexion, respectively) in performance for those patients receiving the standard CON rehabilitation.

In general, the group mean peak relative difference in improvement of patients’ knee RFD associated with NCON versus standard CON conditioning at 48 weeks post-surgery was 7.9% and 15.3% of baseline non-injured leg’s RFD scores during knee extension and flexion, respectively.
5.4.2.4 Neuromuscular performance - electromechanical delay (EMD)

Factorial analysis of variance with repeated measures showed significant leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) \((F_{(1.5, 93.2})^{GG} = 155.9; \ p<0.005)\) and group (NCON; CON) by leg \((F_{(1.6, 97.5})^{GG} = 11.0; \ p<0.005)\) interactions for EMD scores elicited from the knee extensor musculature. The findings suggested that patterns of improvement in EMD over time were different for injured and non-injured legs and that NCON conditioning offered enhanced patterns of recovery compared to CON that were similar in extent over time for knee extensor EMD performance.

A priori ‘difference’ testing of hypotheses for relatively greater progressive improvements in knee extensors EMD over the period of assessment for the injured compared to the non-injured leg was confirmed (29.0 ± 11.7 ms versus 59.5 ± 18.4 ms and 32.7 ± 13.2 ms versus 60.8 ± 22.4 ms [48 weeks post-surgery versus pre-surgery] for the injured leg of patients in the NCON and CON groups, respectively; and 27.4 ± 10.4 ms versus 29.6 ± 12.9 ms and 28.6 ± 13.3 ms versus 29.6 ± 10.8 ms [48 weeks post-surgery versus pre-surgery], for the non-injured leg of patients in the NCON and CON groups, respectively; \(F_{(1, 62)} > 77.3; \ p<0.005)\), [Figure 5.8].

Furthermore, the group mean scores associated with the significant interaction between the factors of leg and group (and a lack of evidence for group x time, and group x time x leg interactions) showed that the overall extent of improvement in EMD performance (i.e. a decrease in scores) was more prominent in both legs for those patients undertaking the NCON conditioning rehabilitation compared to the standard CON therapy, and that this differential in
performance was not influenced by the point in time at which it had been measured.

The peak effects associated with this comparison during rehabilitation ([mean score post-surgery – mean score pre-surgery]/pooled standard deviation) were 2.1 and 0.19 gains in the patients’ injured and non-injured leg’s knee extension EMD performance, respectively, for those undertaking NCON conditioning and corresponding 1.58 gain to 0.09 gains in performance for those patients receiving the standard CON rehabilitation.

In general, the group mean peak relative difference in improvement of patients’ EMD associated with NCON versus standard conditioning at 48 weeks post-surgery was 10.1% and 3.2% (injured and non-injured, respectively) of knee extension baseline non-injured leg’s EMD scores.

The patterns of response for the EMD of the knee flexors was similar to that of the knee extensor musculature with significant leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) \((F_{(1.6, 100.4)} GG = 78.2; \ p<0.005)\) and group (NCON; CON) by leg \((F_{(1.0, 62.0)} GG = 8.4; \ p<0.005)\) interactions.

Equivalent a priori ‘difference’ testing showed the largest improvements for the injured leg \((41.6 \pm 13.5 \text{ ms versus } 68.6 \pm 21.3 \text{ ms and } 47.2 \pm 15.1 \text{ ms versus } 70.3 \pm 26.0 \text{ ms [48 weeks post-surgery versus pre-surgery]}\) for the injured leg of patients in the NCON and control groups, respectively; and 37.9 ± 12.0 ms versus 41.4 ± 12.8 ms and 41.0 ± 15.0 ms versus 44.7 ± 14.7 ms [i.e. performance reduction] 48 weeks post-surgery versus pre-surgery, for the non-injured leg of patients in the NCON and CON groups, respectively; \(F_{(1, 62)} > 11.5; \ p<0.001\), [Figure 5.9].
Figure 5.8  Electromechanical delay [EMD] (ms) in the knee extensors (m. vastus lateralis of the injured and non-injured knees, following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.

Figure 5.9  Electromechanical delay [EMD] (ms) in the knee flexors (m. vastus lateralis of the injured and non-injured knees, following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.
Equivalent peak relative effects for knee flexion scores were 1.4 and 0.28 gains in the patients’ injured and non-injured leg’s knee extension EMD performance, respectively, for those undertaking NCON conditioning and corresponding 1.1 gain to 0.25 loss in performance for those patients receiving the standard CON rehabilitation.

In general, the group mean peak relative difference in improvement of patients’ EMD associated with NCON versus standard CON conditioning at 48 weeks post-surgery was 11.9% and 9.2% (injured and non-injured, respectively) of knee flexion baseline non-injured leg’s EMD scores.

5.4.2.5 Neuromuscular performance - sensorimotor performance (SMP)

Factorial analysis of variance with repeated measures showed significant leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) \( F_{(1.1, 69.9)}^{GG} = 78.6; p<0.005 \) and group (NCON; CON) by leg (injured/non-injured) \( F_{(1.0, 62.0)}^{GG} = 7.3; p<0.01 \) interactions for force error (FE) elicited from the knee extensor musculature. The absence of an interaction between all three factors suggested that while patterns of improvement in sensorimotor performance (SMP) over time were dependent separately on which leg was being assessed and under which regime of rehabilitation conditioning had taken place, the extent of rehabilitation regime-related difference in SMP of the injured and non-injured legs remained at a similar level across the period of study. The latter was therefore characterised by progressive improvements in performance, but was not influenced exceptionally by particular phases of the rehabilitation. The patterns of SMP responses for the knee flexor musculature were similar with significant leg by test occasion
(F_{1.1, 69.9})_{GG} = 78.6; \ p<0.005\) and group by leg (F_{1.0, 62.0})_{GG} = 7.3; \ p<0.01\) interactions being prominent.

Group mean force error scores associated with the NCON versus contemporary CON rehabilitation suggested that superior extent of either maintaining or re-establishing SMP capability in the knee extensor and flexor musculature across the period of follow-up [pre-surgery to 48 weeks post-surgery] (for example, 4.6 ± 2.5 % versus 18.6 ± 7.3 % and 6.4 ± 2.8 % versus 18.4 ± 9.7 % [48 weeks post-surgery versus pre-surgery] for the knee extensors of the injured leg in patients within NCON and control groups, respectively; and 4.8 ± 2.4 % versus 4.5 ± 2.1 % and 5.2 ± 2.9 % versus 4.9 ± 2.7 % [48 weeks post-surgery versus pre-surgery] for the non-injured leg of patients in NCON and control groups, respectively), contributed most to the overall significant interaction, [Figure 5.10].

Equivalent group mean scores for the knee flexors were 8.3 ± 2.5 % versus 21.2 ± 9.9 % and 8.8 ± 2.9 % versus 22.5 ± 7.4 % [48 weeks post-surgery versus pre-surgery] for the injured leg in patients within NCON and CON groups, respectively; and 8.4 ± 2.6 % versus 8.0 ± 2.1 % and 8.8 ± 2.9 % versus 8.5 ± 2.8 % [48 weeks post-surgery versus pre-surgery] for the non-injured leg of patients in NCON and CON groups, respectively [Figure 5.11].

The peak effects associated with this comparison during the rehabilitation ([mean score post-surgery – mean score pre-surgery]/pooled standard deviation) were 2.9 and 1.8 gains (knee extensor and flexor performance, respectively) in the patients' injured leg's FE performance for those undertaking NCON conditioning and 1.9 and 2.5 gains for those patients receiving the standard rehabilitation.
In general, the group mean peak relative difference in improvement of patients’ SMP associated with NCON versus standard conditioning at 48 weeks post-surgery was 5.6% and 4.7% of baseline non-injured leg’s peak force scores during knee extension and flexion, respectively.

Figure 5.10  Sensorimotor performance [SMP] measured as a percentage of force error [FE] (knee extensors) in both the injured and non-injured knees, following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.
Figure 5.11 Sensorimotor performance [SMP] measured as a percentage of force error [FE] (knee flexors) in both the injured and non-injured knees, following ACL reconstruction surgery from pre-to 6, 12, 24 and 48 weeks post-surgery.

5.5 Assessor-patient interactions

The potential influences on function and musculoskeletal and neuromuscular performance of clinico-social approbation by patients associated with increased assessment assessor-patient interactions was assessed using separate ANOVAs involving factors of group (NCON; CON [matched assessor-patient interaction with experimental condition]; Limited testing CON [minimal assessor-patient interaction compared to experimental condition]) by test occasion (pre-surgery versus 48 weeks post-surgery) with repeated measures on the last factor.
5.5.1 Changes in the objectively-measured primary outcome of function (HOP) and the influence of assessor-patient interactions

An ANOVA with repeated measures confirmed that while patients in both experimental NCON and both control groups (CON and Limited testing CON) improved function during the follow-up period, group mean scores associated with NCON rehabilitation were superior. However, the patterns of change were not significantly different between the CON and Limited testing CON groups, pre-surgery versus 48 weeks post-surgery ($F_{(2.0, 79.0)} GG = 18.5; p<0.005$). This provides no evidence that clinical approbation by patients had contributed significantly to single-leg hop performance and so superior objective functional performance might be properly attributed to the effects of the NCON rehabilitation ($F_{(2.0, 79.0)} GG = 18.5; p<0.005$).

5.5.2 Changes in the objectively-measured secondary outcomes of musculoskeletal and neuromuscular performance and the influence of assessor-patient interactions

Patterns of change within the secondary musculoskeletal and neuromuscular outcomes of ATFD, PF, RFD, EMD and SMP associated with the knee extensors and flexors of the injured and non-injured legs, (i) increased clinical effectiveness of NCON conditioning ($F_{(1.6, 79.1)} GG = 4.5 to 19.7; p<0.01$) and (ii) showed that Improvement patterns were not significantly different between matched and minimal assessment assessor-patient interaction control groups (CON vs. Limited testing CON; pre-surgery versus 48 weeks post-surgery), indicating that clinical approbation by patients had not contributed significantly to the study’s findings.
5.6 Intention to treat

Comparisons using univariate ANOVA of group mean responses for objective outcome measures for the injured leg at pre-surgery amongst Lost to-follow-up (n=19), CON (n=22) and NCON (n=26) groups, respectively, were as follows:

HOP: 95.6 ±19.0, 97.5 ±18.5 and 97.0 ±19.4 cm (F(2,64)=0.7, ns); ATFD: 14.7 ±4.2, 14.2 ±4.3 and 14.4 ±3.9 mm (F(2,64)=1.0, ns); PF[knee extension]: 365 ±49, 360 ±48 and 370 ±50 N (F(2,64)=1.5, ns); PF[knee flexion]: 202 ±42, 206 ±49 and 208 ±51 N (F(2,64)=1.2, ns); RFD[knee extension]: 1420 ±390, 1435 ±370 and 1410 ±365 N·s⁻¹ (F(2,64)=1.3, ns); RFD[knee flexion]: 1120 ±260, 1145 ±290 and 1175 ±300 N·s⁻¹ (F(2,64)=1.1, ns); EMD[knee extension]: 58.2 ±8.1, 57.6 ±7.6 and 59.1 ±7.9 ms (F(2,64)=1.6, ns); EMD[knee flexion]: 64.7 ±17.1, 63.6 ±16.8 and 65.0 ±17.8 ms (F(2,64)=0.9, ns); FE[knee extension]: 18.8 ±6.1, 18.1 ±7.0 and 19.1 ±7.9 % (F(2,64)=0.6, ns); FE[knee flexion]: 22.4 ±4.4, 21.6 ±5.8 and 23.0 ±6.2 % (F(2,64)=1.4, ns).

With the exception of PF associated with the knee flexors (3.2% and 2.4% lower scores for lost to follow-up, injured and non-injured legs respectively (F(3,0, 97.0) GG = 3.9; p<0.05), all the outcomes showed statistically similar performance characteristics at baseline (pre-surgery) amongst the group mean scores for the study groups and those patients who had been lost to follow-up. This suggested that biasing of the data might have intruded in only a minor way within this study.
5.7 Discussion

This is the first study to have investigated the effects of a new design in post-operative rehabilitation (NCON) on objectively-measured functional, musculoskeletal and neuromuscular performance outcomes pertaining to dynamic joint stability. The study was designed to offer the equivalent volume and intensity of rehabilitative exercise across the study groups. This ensured differences found were as a result of the intervention and not due to overtraining effects. In addition, a third control group investigated and excluded the contribution of, the potential bias resulting from the increased assessor-patient interaction during the study assessment periods. The duration of the study and the assessment occasions were applicable to the healing process of the autologous graft tissue and the progressive phases of rehabilitation. The formal rehabilitation was completed by 24 weeks, however a 48 weeks assessment occasion was included to address the time when patients return to what they consider normal function without any clinical restraint.

In order to test the effects of this novel formulation of NCON rehabilitation following ACL-reconstruction, functional (HOP), musculoskeletal and neuromuscular (ATFD, PF, RFD, EMD and SMP) outcome measures were used. All of these measures have been used in past research when investigating the dynamic stability of the knee (Risberg 1999, Fitzgerald et al. 2001, Hewitt et al. 2006, Gleeson et al, 2008a, Gleeson et al. 2008b, Minshull et al. 2009, Arderne et al. 2010, Thomee et al. 2011, Minshull et al. 2011).

The results show beneficial gains for all the participants’ injured and non-injured limbs, irrespective of the group to which they had been assigned randomly. However, the specific aim of this RCT was to evaluate the effects of NCON strength and endurance conditioning in comparison to the
contemporary concurrent rehabilitation programme on injured and non-injured legs following ACL reconstruction, by analysing: Primary outcome of function (HOP); Secondary outcomes of musculoskeletal and neuromuscular performance (ATFD, PF, EMD, RFD, SMP). The influence of NCON conditioning during the post-surgical, one-year follow-up was found to be superior to standard CON practice. The study’s findings showed significant group (NCON; CON) by leg (injured/non-injured) by test occasion (pre-surgery, 6, 12, 24 and 48 weeks post-surgery) and condition by test occasion interactions for the primary outcome of function (HOP) together with secondary outcomes of ATFD, PF, RFD, EMD and SMP associated with the knee extensors and flexors of the injured and non-injured legs (p<0.01) and confirmed increased clinical effectiveness of NCON conditioning.

In general, this novel intervention offered improvements in objective measures of function, and in objective indices of physical performance capability that were between ~4.7% and 15.3% better than control between the period 12 and 48 weeks after surgery. The patterns of improvements in physical fitness capabilities across knee extension and flexion performance scores relative effect size range: 0.3 and 0.1 (for example, PF during knee flexion showed the smallest relative effects; NCON and CON, respectively) to 6.0 and 4.8 (for example, ATFD showed the largest relative effects; NCON and CON, respectively) showed partial congruence with significant improvements to objective scores of function, 0.71 and 0.13 (HOP; NCON and CON, respectively) across the 5 assessment occasions (p<0.01). Similar to the patterns of relative effect size for the changes in subjective performance discussed in Chapter 4, the patient follow-up period will have been influenced by the extent of absolute changes over time for the objective outcome
measures used in this study, as well as by heterogeneity of conditioning dose-responsiveness.

The patterns of improvement in the single leg hop tests for both legs were similar to other findings in the literature (Reid et al. 2007) and showed greatest effect when delivered by the NCON conditioning at 12 weeks post-surgery (12.2%). It was interesting that the gains for NCON versus control had diminished by the assessment at 48 weeks post-surgery (6.3%). This pattern of gain in hop performance for NCON conditioning was mimicked in the findings for several of the outcome measures and suggested that the acute phase of rehabilitation appears to have more effect on functional hop performance and the performance of other measures than the later phase of rehabilitation conditioning. Although the advantage gains for NCON conditioning in hop performance were statistically significant, the extent of advantage (6.3%) for this outcome and amongst the others used in this study (~up to 15%) might not confer clinical utility: This advantage might not be sufficient to warrant the re-organisation of the delivery of rehabilitation programmed care to accommodate this new pattern of conditioning, despite the observed low to moderate improvement in outcomes.

Muscle strength (PF) will be negatively affected with injury and following surgery (Hopkins and Ingersoll 2000, Rice and McNair 2010). One of the main functions of ACL rehabilitation is to restore optimum muscle strength (van Grinsven et al. 2010, Lobb et al. 2012, Manske 2012). All groups showed improvements in strength for both knee flexors and extensors over the 48 weeks. The group mean peak relative defence of improvement between the experimental and control was 5.4% (knee flexors) and 5.9% (knee extensors) at 48 weeks. As alluded to earlier in the discussion for hop performance, the
acute phases of recovery (6 and 12 weeks post-operatively) were more prominent: for injured leg knee extensors, 6 weeks post-surgery versus pre-surgery ($p<0.05$). This pattern of response is congruent with those from other studies in the literature (Gleeson et al. 2008). Estimates of muscle activation performance, including RFD and EMD, improved over time in all of the groups, predominantly in the injured leg, and most prominently in the NCON experimental group, with a group mean relative difference improvement of between 7.9% for knee extensors and 15.3% for the knee flexors at 48 weeks post-surgery. Again, the majority of the improvement was gained between pre-surgery and 12 weeks post-surgery.

In comparison with the self-perceived outcomes (IKDC and KOOS) presented in Chapter 4, a number of the objective outcomes (HOP, PF flexors, RFD) also demonstrated greater interactions during the acute phase of rehabilitation (12 weeks assessment occasion). The reasoning identified previously for subjectively-measured outcomes of function (Chapter 4), that with patients returning to their full time employment at 6 to 12 weeks post-surgery, the time available for patients to perform the same volume of rehabilitation would have been limited from then onwards, might also explain why there had been a diminishing pattern of gain in objectively-measured physical fitness and function identified in this chapter. Likewise, the dose-responsiveness in rapid recovery from a deconditioned state to a slower response as near-normal parameters are re-established suggested for the self-perceived outcome measures of function at this stage, might also be applicable to the objective measures. Anecdotally, at this phase in the rehabilitation, some individuals do not enjoy the types of exercises required to re-establish musculoskeletal and neuromuscular performance, or they find attending leisure
centres or private gyms difficult, and preferring instead to participate in outdoor recreational activities that do not necessarily promote significant musculoskeletal and neuromuscular outcomes.

Sensorimotor performance (SMP) is the only neuromuscular measure that has been causally linked with ACL injury (Caraffa et al. 1996, Hewett et al. 2006, Griffin et al. 2006). However, the significance of SMP has come under scrutiny recently, with some researchers suggesting that it isn’t as clinically relevant as previously speculated in the literature (Gokeler et al. 2012). Previous research, that has led to this conclusion, measured either passive joint motion detection or joint position sense (Gokeler et al. 2012). This study tested force reproduction as a measure for SMP, which might be more significantly associated with dynamic knee joint stability. Greater improvements were seen in the experimental group from pre-surgery to 48 weeks post-surgery for both knee flexors and extensors. So, unlike the previously mentioned performance measures, SMP continues to improve significantly up to 48 weeks post-operatively. Perhaps a reason for this might be that normal activities of daily living have a substantial role in SMP promotion, and more-so than in musculoskeletal performance. Or possibly, as the graft tissue remodels over time, it is infiltrated with mechanoreceptors, which might improve the sensorimotor performance at the joint (Duthon et al. 2006, Oryan et al. 2013). It is an interesting and important point that SMP, as in other functional and performance outcomes, have not returned to the pre-surgery capability of the non-injured leg by the end of the follow-up, indicating potentially, a continuing relative risk of re-injury if the patient has re-commenced stressful physical activities.
Anterior cruciate ligament reconstructive surgery in this study was performed by two very experienced consultant orthopaedic and sports injury surgeons. The autologous graft tissue used for the reconstruction surgery was either patella tendon or a combination of semitendinosus and gracilis tendons in order to restore the passive restraint of the knee. Anterior tibio-femoral draw (ATFD) is a common-place test for the continuity of the ligament/graft (Beynnon et al. 2005). The findings from this study found an advantageous decrease in ATFD at 48 weeks post-surgery particularly for the participants in the experimental group, with a 14.2% improvement above the outcome of traditionally rehabilitated control group. The patterns of change in knee laxity in this study matched those elsewhere in the literature during the acute phase of rehabilitation (up to 10 weeks; Gleeson et al. 2008). The reason why passive knee joint laxity reduces especially to a greater extent in the NCON trained group is not fully understood. It might be speculated that increases of musculoskeletal and neuromuscular outcomes in the acute phase of rehabilitation establishes a better dynamically controlled knee joint whilst the graft tissue is healing, and from which subsequent enhanced gains in ligamentous robustness can emerge.

Additionally, the improvements in self-perceived performance (most significantly at 12 weeks post-surgery, presented in Chapter 4) might give the patients increased confidence to simultaneously train harder, and giving rise to greater objective gains. This might also be self-perpetuating as improvements in self-perceived function could drive increases in objective outcomes or vice versa. The following chapter investigates if any significant relationships exist between self-perceived (subjective) and objective outcomes which might in
turn, offer insight into what drives function and whether the result of one outcome could predict that of another.

5.8 Conclusion

Once again, improvements were seen in all outcome measures following ACL rehabilitation, irrespective of the study group to which they had been allocated randomly. As the rehabilitation is holistic in design, it is not surprising that both the injured and non-injured limbs demonstrated musculoskeletal and neuromuscular improvements. However, the injured limb did show greater gains, possibly due to the potential inherently for greater gains associated with the increased level of pre-operative deconditioning and inhibition from the ACL injury and surgery, together with the immediate post-surgery, protective clinical care restrictions placed upon it. Ultimately this study provides evidence that NCON rehabilitation is superior to traditional CON practice. Therefore, the null-hypothesis associated with study and primary aim for the thesis of *similar objective functional, musculoskeletal and neuromuscular gains as measured by HOP, ATFD, PF, RFD, EMD and SMP, will be accomplished by rehabilitating from ACL surgery over time in a NCON format compared to the traditional phasing of concurrent (CON) conditioning*, can be rejected.

These findings correspond to the greater improvements in self-perceived outcomes of functional capabilities, especially in the acute stages of recovery, when NCON rehabilitation is adhered to (present in Chapter 4). The implication of superior objectively-measured functional, musculoskeletal and neuromuscular performance in the acute phase of recovery gained by NCON rehabilitation, might suggest the possibility of accelerating the rehabilitation process and/ or, it might provide improved function, preventing further injury.
However, the overall improvement from this altered sequencing of rehabilitation prescription centres around ~10% for all musculoskeletal and neuromuscular measures. Despite the iso-volumetric approach used in this study to match groups experimentally, it could be argued that this advantage associated with NCON conditioning might not be enough of an improvement to justify the logistics of initiating changed clinical practice that might incorporate the enhanced approach to rehabilitation conditioning.

Nevertheless, both the self-perceived (subjective) and objective outcomes measuring function, musculoskeletal and neuromuscular performance are better when NCON rehabilitation is followed compared to the traditionally prescribed CON conditioning. Likewise, both the subjective (IKDC and KOOS) and objective (HOP, PF flexors and RFD) outcome measures show greater interaction during the acute phases of recovery from ACL surgery (12 weeks), alluding to possible relationships between subjective function, objective function, musculoskeletal and neuromuscular performance. Therefore, the following chapter analyses the correlations between subjective functional (IKDC), objective functional (HOP) and musculoskeletal and neuromuscular outcomes, in the same population of patients.
Chapter 6:
Correlations between Subjective Functional and Objective Functional, Musculoskeletal and Neuromuscular Outcomes in Patients with Anterior Cruciate Ligament Deficiency
6.1 Chapter abstract

Title: Correlations between subjective functional and objective functional, musculoskeletal and neuromuscular outcomes in patients with anterior cruciate ligament deficiency.

Context: Both subjective (self-perceived) and objective outcome measures are commonly used following ACL injury to assess knee function and they are key indicators of when to return to sport. Objective measures can be over-burdening and expensive in terms of equipment and assessor time. Therefore, if a robust and significant relationship exists between an easily-delivered and inexpensive subjective outcome score of function, the aforementioned objective measures could be made redundant. Additionally, the assessment of the strength of relationship between subjective and objective measures might offer insight into the congruence between these approaches to the assessment of function. Relationships between changes in outcomes of function and physical performance capabilities over time might identify mechanisms of change in functional capacity and therefore, inform enhancements to the composition of post-surgical rehabilitation. Objective: To explore the relationships amongst subjective (self-perceived) measure of knee function (International Knee Documentation Committee [IKDC] knee evaluation form, a primary outcome measure of the thesis) and objective measures of function (single-leg hop for distance [HOP]), musculoskeletal (anterior tibio-femoral displacement [ATFD; knee laxity]), neuromuscular performance (peak force [PF, strength], rate of force development [RFD], electromechanical delay [EMD]), force-error [FE]), at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery.
Setting: Orthopaedic Hospital NHS Foundation Trust. Design: Randomised control; pilot study. Participants: Sixty four patients (56 males, 8 females; age: 37.1 ± 8.9 yr; height: 1.77 ±0.08 body mass: 81.8 ±11.7 kg; time from injury to surgery 8.8 ± 6.8 months [mean ± SD]; 16 lost to follow-up) were randomly allocated to NCON: CON (1:1). Interventions: A standardised traditional concurrent (CON) ACL rehabilitation programme acted as the control versus an experimental non-concurrent (NCON) ACL rehabilitation programme that involved separation of strength and cardio-vascular endurance conditioning. Main Outcome Measures: Self-perceived (IKDC) subjective knee evaluation and the objectively-measured outcome of function (HOP), and selected objectively-measured outcomes of musculoskeletal and neuromuscular performance including ATFD, PF, RFD, EMD and SMP of the knee extensors and flexors of the injured and non-injured legs were measured at pre-surgery and at 24 weeks post-surgery. Outcomes were analysed for association, using Pearson product-moment correlation coefficients. A priori alpha levels were set at p<0.05. Results: Two-tailed probabilities were used due to the exploratory nature of this study. A limited number of weak to moderate statistically significant correlations were confirmed (ranging from r = 0.262 – 0.404; p<0.05) between IKDC and most notably, the neuromuscular performance outcome of EMD. Conclusions: The IKDC subjective knee evaluation score is not robustly correlated with an objective outcome measure of function (HOP) and subjective functional capacity cannot be predicted confidently from the objectively-measured outcomes of musculoskeletal or neuromuscular performance to a level required for clinical practice (r² <0.16). Given that most outcomes have been shown to be unrelated to one another and cannot be shown to be redundant, all of the outcomes should be included within a multi-variable model.
of assessment in order to fully assess and describe the effectiveness of rehabilitation.

6.2 Introduction

It is important to use standardised outcome measures in research and clinical practice in order to evaluate the effectiveness of therapeutic interventions, thus providing evidence based practice and informed decisions on treatment (Reid et al. 2007, Bent et al. 2009). In addition, Keays et al. (2003) states that the development of definite and precise rehabilitation guides is dependent on the clarity of understanding of all outcome variables associated with neuromuscular control of the knee. Furthermore, practitioners need to be familiar with a range of measures and the validity and reliability of those measures in order to provide effective evidence based treatment (Bent et al. 2009). However, many NHS hospitals do not have access to potentially expensive equipment to measure musculoskeletal and neuromuscular outcomes. Therefore, if a simple inexpensive subjective outcome score (the International Knee Documentation Committee (IKDC) subjective evaluation form, for example) could provide clinically significant correlations with labour-intensive objective outcome measures, it could lead to the redundancy of expensive objective assessment procedures. In addition, how a subjective measure relates to an objective measure might offer insight into whether one approach to outcome assessments offers greater validity in the prediction of functional success than another.

There are a number of subjective/ self-perceived outcome measures used in clinical practice. Collins et al. (2011) provides a concise review of some of the most common, including the International Knee Documentation
Committee (IKDC) subjective knee evaluation measure, the Knee injury and Osteoarthritis Outcome Score (KOOS), the Knee Injury and Osteoarthritis Outcome Score Physical Function Short Form (KOOS-PS), the Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL), the Lysholm knee scoring scale, the Oxford Knee Score (KOS), the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the Activity Rating Scale (ARS) and the Tegner Activity Score (TAS). The review provides a succinct description including the practical application of each outcome measure. In addition, the psychometric information is reported and a critical appraisal of the overall value for each measure of subjective function is discussed. Over the past years, and to the present day, all of these measures have been deployed separately to establish surgical and rehabilitative success and to give an indication on a safe return to sport and function (Roos et al. 1998, Irrgang et al. 2001, Lohmander et al. 2004, Collins et al. 2011, Irrgang et al. 2012). In contrast, objective measures of functional performance, such as muscle strength and hop tasks, are also considered as key markers of successful rehabilitation and when it is an appropriate time for the patient to return to full activity (Fitzgerald 2000, Clark 2001, Hopper et al. 2002, Gustvasson et al. 2006, Reid et al. 2007, Thomeé et al. 2011). However, only limited research scrutiny of relationships between subjective inventories and objective estimates of function performance has been reported. Research has been focused only on long-term outcomes (Ageberg et al. 2008, Ardern et al. 2010) or short epochs within the rehabilitation process (Reid et al. 2007, Gleeson et al. 2008).

It is acknowledged that rupture of the anterior cruciate ligament (ACL) is serious and common place. Nevertheless, discrepancies on the timing of a safe return to function still remain in the literature (Griffin et al. 2006). Bjordal (1997)
reports the advancement of ACL reconstructive surgery and subsequent rehabilitation means sustaining an ACL rupture is no longer thought to be a career threatening injury. However, Ardern et al. (2011a) reported a failure to restore functional capability in the knee at 12 months follow-up is reported to occur in 67% of patients electing to undergo reconstruction surgery. A meta-analysis investigating the return to sport following ACL injury found only 63% established pre-injury levels of sporting function (Ardern 2011b). Therefore, a better understanding of when it is safe to return to function following rehabilitation for this population is of clinical and social significance. This is especially so, as the consequences of ACL injury and time to return to full function can incur direct (surgery, medical care, management and rehabilitation) and indirect (time lost from work, decreased productivity) costs (Zelle at al. 2005, Paxton at al. 2010).

Furthermore, altered sensory feedback from the autologous ACL graft and inhibited neuromuscular performance due to pain and swelling have been shown to disturb neuromuscular co-ordination at the knee (Hopkins and Ingersoll 2000, Krogsgaard et al. 2011, Rice and McNair 2010). These processes might be expected to provoke potentially novel sensations and sensorimotor challenges to the patient during rehabilitation and conditioning. Anterior cruciate ligament rupture and its subsequent surgical reconstruction offers by means of serendipity, an important environment for the assessment of inter-relationships amongst functional, physical and psychological responses. These responses are likely to be amplified compared to those associated with asymptomatic populations, with a substantive progression from low conditioning (injured) to high conditioning (restored function) status (Gleeson et al. 2008). The extent and patterning of these subjective functional, musculoskeletal and
neuromuscular changes (while offering potentially greater absolute effect size) might be compromised in relative effect size because of greater heterogeneity of responses among patients compared to asymptomatic counterparts. Amongst this process of recovery, any novel sensations resulting from altered knee function, might create further challenges for the patient when he/she attempts precise scaling of the demands of exercise.

In a systematic review by Ardern et al. (2012), fear was found to be the most fundamental factor that would hold an athlete back from full function. An accumulation of factors of negative mood, patient’s perception of their capabilities, including a lack of confidence in the knee and fear of re-injury, have been considered as regulators of the rate at which function might be restored (Heijne et al. 2007, Brewer at al. 2007, Webster et al. 2008, Ardern et al. 2012). Notably, self-efficacy of knee function has been reported as a strong predictor of long-term outcomes following surgery (Thomeé et al. 2008). Differences in self-efficacy have been shown to modify perceptions of effort during exercise (Hu et al. 2007), leading to the potential for hypo- or hyper-dosing of exercise stress and volume. Potentially, the negative psychological factors associated with the patients’ subjective performance capability might in turn cause tentative physical and psychological responses to rehabilitation and return to function.

Although amongst a range of musculoskeletal and neuromuscular factors, only sensorimotor performance has been linked causally to reduced rates of injury (Caraffa et al. 1996, Hewett et al. 2006, Griffin et al 2006), understanding of the patterns of relationship and correlation amongst subjective and objective factors and the relationship to functional capability might offer important insights regarding the mechanisms of altered perception of effort and injury risk regulatory mechanisms.
Overall, the subjective capability for precise self-perception of physical capabilities is becoming increasingly important in gauging progress towards a return to pre-injury activity levels and audit of clinical process, especially when contextualised amongst governmental and clinical drivers increasingly towards for primary and self-managed care of patients. Precise perception and self-regulation of work-rate is particularly important for patients undertaking rehabilitation sessions in the absence of specialist supervision. Patient-reported subjective measures of knee function are routinely used in a clinical environment to help monitor the progress of rehabilitation (Collins et al. 2011, Adams et al. 2012). Nevertheless, an important underpinning premise would be that patient-perceptions of functional capability are congruent with objective assessments of function. Disassociation between subjective and objective indices of function and altered capability perceptions of musculoskeletal and/or neuromuscular factors that might determine functional capability, would be hypothesised to provoke sub-optimal conditioning during rehabilitation with the mis-matching of perception. This gives potential for patients to underestimate or overestimate their sense of effort and thus impact on their regulation of the intensity and volume of exercise during rehabilitation, leading to compromised outcomes.

Correlations between hop test scores and subjective measures of function, provided by either or a combination of Cincinnati knee scale, Lysholm, International Knee Documentation Committee (IKDC) evaluating system and Tegner activity scale, were reported in a review by Fitzgerald et al. (2000). The review provides correlates for self-perceived, subjective function as measured by IKDC, Cincinnati Knee Scale, Lysholm and Tegner with single leg hop ranging from \( r = 0.03 \) – 0.48. Fitzgerald et al. (2001) concludes that the
relatively low correlations between hop test scores and subjective outcome measures means neither one approach to assessment could be a stand-alone measure of functional performance and goes on to suggest each measurement might be capturing a different aspect important to function.

Reid et al. (2007) investigated the reliability and longitudinal validity of data obtained from hop test during rehabilitation following ACL reconstruction. Forty-two patients participated in the prospective study that had involved repeated-measures. Four types of hop tests were included - single hop for distance, 6 metre timed hop, triple hop for distance and cross over hop for distance. The Lower Extremity Functional Scale (LEFS) was used to measure subjective function following the hop tests. These tests were performed on four separate occasions; the first three were within the 16th week post-surgery (separated by a minimum of 24 hours) and the fourth 6 weeks later. The study showed there was a significant effect for time ($p<0.001$). Absolute hop scores of the first test occasion were significantly different from those on the second test occasion ($p<0.01$). However, there was no significant difference in absolute scores completed on the second and third test occasions ($p>0.89$) and with the exception of the timed hop ($p = 0.17$), but there was a significant difference between the second and fourth test occasions ($p<0.001$). The relatively low levels of correlation between subjective and objective tests of function and performance using either cross-sectional or change scores, might challenge the utility of either or both of the approaches to the evaluation of rehabilitation progress. Indeed, it is implied that more than 80% of the variance in scores associated with comparisons between subjective and objective tests of function, are determined by factors other than those that are common to both approaches to evaluation, which is in accordance with Fitzgerald et al. (2000).
Other commentators such as Ardern et al. (2010), have also demonstrated variance and dis-association between subjective and objective measures in patients electing ACL-reconstruction surgery, and how this appears to impact on the rates of patients returning to sport at 12 months post-surgery. Patients showing less difference in objective performance between injured and non-injured contra-lateral control limbs (>85% of non-injured limb performance; n = 423; 84% of sample populations) were found to be more likely to return to sport than those exhibiting greater disparities (<85% of non-injured limb performance; n = 80; 16% of sample population). It was interesting to note that in contrast, patients self-reporting normal or nearly normal knee function by means of the subjective inventory IKDC (n = 468; 93% of sample population) were no more likely to return to competitive sport than patients reporting poor function (n = 35; 7% of sample population).

Additionally, a patient’s perception of capability might be modified towards achieving more effective scaling of subjective and objective capabilities is via interaction with expert physiotherapists. The influence of the physiotherapist on patients through clinical and social approbation might be substantive and possibly enhance outcomes. It is for this particular reason, that the experimental design for the research used in this thesis includes an additional ‘control’ (Limited testing NCON). The assessor influence was quantified by purposefully minimising assessor-patient interaction by limiting the follow-up assessment occasion to one (48 weeks post-surgery). The relevant methodology was described in Chapter 3 – Section 3.2.5.

Nevertheless, while the latter is an important consideration, the potential impact of the physiotherapist on patient outcome and psychological health during the period of rehabilitation is tempered by the patient receiving and
benefitting from only limited contact time with a physiotherapist (less than 20 session during a post-operative ACL rehabilitation period; 6-9 months). Therefore, patients do have to perform self-management of the majority of rehabilitative exercise in an unstructured environment (Coppola and Collins 2009).

When attempting to identify levels of ‘normal’ or improved function brought about by surgery and subsequent rehabilitation, the use of the contra-lateral asymptomatic leg as a baseline and control is prevalent and indeed, was used in this way in the intervention study within this thesis. There are caveats to the unreserved use of the contra-lateral limb as a reference for the injured limb because of the potential for deconditioning associated with injury-related alterations to physiological loading, limb dominance discrepancies, and bi-lateral neurophysiological (de)conditioning (Gleeson 2008). Nevertheless, the notion of functional and performance symmetry between injured and non-injured limbs has been favoured in the literature (Borsa et al. 1998, Hopper et al. 2002, Ardern et al. 2010, Thomee et al. 2011), with patients who demonstrate an acceptable level of symmetry (85% to 100%, Ageberg et al. 2008, Ardern et al. 2010, Thomeé et al. 2011) considered more likely to return to sport (Fitzgerald et al. 2000, Ageberg et al. 2008, Ardern et al. 2010).

It is possible that any discrepancies between subjective perception and objective findings might translate to a detrimental effect on patients’ rehabilitation; patients might fail to meet criterion training goals leading to even greater delays to progress onto the subsequent phase of rehabilitation (van Grinsven et al. 2010).
The purpose of this study was to explore the relationships amongst:
The subjective (self-perceived) measure of knee function (International Knee Documentation Committee [IKDC] knee evaluation form, a primary outcome measure of the thesis) and objectively-measured outcome of function (single-leg hop for distance [HOP]), musculoskeletal performance (anterior tibio-femoral displacement [ATFD; knee laxity]) and neuromuscular performance (peak force [PF, strength], rate of force development [RFD], electromechanical delay [EMD]), force-error [FE]), at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery.

Correlations focused on absolute scores associated with the specified outcome measures, scores associated with injured versus non-injured (contralateral) limb differences and scores representing patterns of change over time for the injured limb.

6.3 Methods

6.3.1 Participants

The participants included in this chapter vary slightly from the main randomised control trial presented in Chapter 3 – Section 3.2.5. For the purpose of this correlation chapter, only the data from the CON and NCON groups were analysed. The additional control group (Limited testing CON) was not included, because this group was purposefully not followed up at the 24 weeks post-surgery assessment occasion.

Therefore, 64 of the consented patients were included in this correlation study (56 male, 8 female [age: 37.1 ± 8.9 yr (range 19 to 50 yr); height = 1.77 ±
0.08 m; body mass = 81.9 ±11.7 kg; time from injury to surgery 8.8 ± 6.8 months]; n = 16 lost to follow-up). All the patients elected to undergo unilateral ACL-reconstructive surgery (semitendinosus and gracilis graft or central third, bone-patella tendon-bone graft) at a U.K. National Health Service Foundation Trust hospital and gave their informed consent to participate in the study (for inclusion/exclusion criterion refer to Chapter 3 – Section 3.2.2). Patients were treated by two consultant orthopaedic surgeons (DR; SR) of similar experience and practice (> 12 ACL reconstruction surgeries per month) using agreed and matched surgical procedures. Upon meeting the inclusion criteria patients were invited to partake in the study [Chapter 4, Table 4.1 provides a summary of the inclusion/exclusion criteria]. A summary of the patients allocated to this study is presented in the consort diagram, Figure 6.1.

6.3.2 Ethical approval

This study met the ethical standards suggested by Harriss and Atkinson (2009), and the study was approved by the Ethics Committee for Human Testing of the University of Exeter, UK, and by the Shropshire area NHS Ethics Committee (REC reference 05/Q2601/36) and had received scientific merit approval from the Research Committee of the applicable Orthopaedic Hospital NHS Foundation Trust, UK. The study can be tracked using the reference code R5613 with respect to The National Institute for Health Research (NIHR) Clinical Research Network (CRN).
Figure 6.1 Consort Diagram for correlation analysis – summary of the number of patients recruited, the random allocation and those lost to follow-up.
6.3.3 Rehabilitation

The programme of rehabilitation comprised a standardised and established (>5 yr) structured and supervised rehabilitation conditioning [705 ± 10 minutes]), focusing on progressive mobility, strength and endurance conditioning. As part of the overall programme of research, patients had been allocated randomly to two modes of iso-volumetric rehabilitation conditioning. Conditioning was matched in all aspects of delivery with the exception of a systematic manipulation of the sequencing of the patient’s exposure to strength- and endurance-related exercises (further details are presented in Chapter 3 – Section 3.3).

The precise dosing, volume and intensity of rehabilitation was controlled by patient self-monitoring of his/her own physical rehabilitation activities by weekly self-report diaries, with physiotherapist verification of dosing within formal and structured rehabilitation sessions throughout the assessment period. Patients were asked to record the number and type of rehabilitation sessions completed each day and the total daily time spent performing physical activity. Patients were not given feedback of results until after the completion of the prescribed number of test occasions.

6.3.4 Assessment procedures

The experimental design for assessment of relationship responses were collected at baseline (pre-operative, ≈2 weeks prior to surgery) and at 24 weeks post ACL reconstruction surgery as this marked the completion of the formal ACL rehabilitation period. The relationship protocol is illustrated schematically in Figure 6.2.
The data was collected from the main randomised control trial and this is reported in Chapters 4 and 5. The same general methods were followed as described in Chapter 3. The methodology varied from the main study (presented in Chapters 4 and 5), as the correlational data was derived only from functional and physical performance capability assessments undertaken at baseline (pre-operatively) and at 24 weeks post ACL reconstruction surgery. The data from the 6, 12, and 48 weeks assessment occasions were not examined. The assessment occasions used for correlational analyses (pre-surgery and 24 weeks post-surgery) were decided upon as follows: The pre-operative correlates would offer a baseline of relationships in the unstable ACL deficient knee. The correlations at 24 weeks post-ACL reconstruction surgery by comparison, would have offered insight into the relationships between the selected indices at the completion of formal rehabilitation and return to restriction-free function of the surgically stabilised knee.

The first assessment session included time for patients to become familiarised with the assessment procedures and protocols. During this initial
meeting with the researcher (≈2 weeks prior to surgery) and at subsequent assessment session of 24 weeks following surgery, each patient was assessed for primary outcomes of function (HOP; IKDC) together with secondary outcomes of musculoskeletal and neuromuscular performance. These included anterior tibio-femoral displacement (ATFD), peak force (PF), rate of force development (RFD), electromechanical delay (EMD), and sensorimotor performance (SMP) associated with the knee extensors and flexors of the injured and non-injured legs.

Assessments and the order of testing legs were undertaken in a random sequence (computer generated). While these indices of physical assessment measures (ATFD, PF, RFD, SMP, and EMD) would not be readily available within contemporary clinical practice, the inclusion of these measures might allow an understanding of musculoskeletal and neuromuscular performance, during recovery and rehabilitation following ACL surgery (Gleeson et al. 1996, 2001, 2005, Minshull et al. 2007). Prior to all testing, patients undertook a standardised warm-up protocol, that involved five minutes of cycle ergometry (90 watts for males, 60 watts for females, or as tolerated clinically by patients), and a further five minutes of static stretching of the involved musculature. Patients were then secured in a seated position on a custom-built dynamometer (Gleeson et al. 1992) and arthrometer (Gleeson et al. 1996).

6.3.5 Outcome Measures

The relationships amongst the subjective perception of function (IKDC) and those of objectively-measured function (HOP) and musculoskeletal and neuromuscular performance (ATFD, PF, RFD, EMD, SMP) were of clinical interest. If a simple, questionnaire-based knee evaluation of functional
capability was found to relate robustly to objective measures of function, then it might allow the clinician to predict safe return to function without the requirement of having to rely on sophisticated, expensive and time-consuming objective measures. The IKDC knee evaluation form has been shown to be a valid and reliable measure and was chosen above all others, due to its specificity in knee ligament assessment (Hambly 2010, Collins et al. 2011, Irrgang et al. 2012). It is also one of the most common subjective measures of function used in ACL literature (Collins et al. 2011, Irrgang et al. 2012).

The patient and dynamometer orientation, the primary indices of function (IKDC and HOP) and the secondary musculoskeletal and neuromuscular indices (ATFD, PF, RFD, EMD, SMP) are outlined fully in Chapter 3 – Sections 3.5.1, 3.6, 3.7 and 3.8.1 – 3.8.4.

In summary, the 18 questions and/or rated-statements contained in the IKDC form was completed by the patient. The assessor was available to answer any questions regarding terminology and did not prompt the patient in any way which might have biased the score. Hop for distance was calculated as the mean of three efforts. Joint laxity, as measured by ATFD, used a system that has previously been shown to be valid and reliable (Gleeson et al. 1996). Peak force for both the knee extensors and flexors was identified following a series of 3 intra-trial replicates of maximal volitional muscle activation (MVMA) (Gleeson et al. 1996, Minshull et al. 2009, 2011). Electromyographic activity (EMG) was recorded using surface electrodes over m. vastus lateralis and m. biceps femoris. Rate of force development was calculated as the average rate of force increase between 25% and 75% of PF. Electromechanical delay (EMD) was measured as the first point in time where the recorded signals exceeded consistently the 95% confidence limits of the
background electrical noise amplitude (Minshull et al. 2009, 2011) and the onset of force during the MVMA. Sensorimotor performance (SMP) was judged by force error (FE) in the ability to reproduce a predetermined and blind target force (50% of pre-operative PF).

### 6.3.6 Statistical analyses

The relationships amongst the selected subjective measure of knee function (IKDC) and the objective measure of function (HOP) and indices of musculoskeletal and neuromuscular performance recorded at baseline (=2 weeks prior to surgery) and at 24 weeks post ACL surgery were assessed.

Firstly, relationships amongst subjective and objective outcome measures of function, and outcomes of musculoskeletal and neuromuscular performance involving absolute scores of the injured leg, were assessed as follows: IKDC and single-leg hop, and between IKDC and anterior tibio-femoral displacement, peak force, electromechanical delay, rate of force development, and force error scores at the pre-surgery and 24 weeks post-surgery assessment occasions.

Secondly, relationships amongst subjective and objective outcome measures of function, and outcomes of musculoskeletal and neuromuscular performance involving injured-contralateral legs were assessed as follows: Difference scores associated with injured-contralateral leg functional or performance comparisons at each assessment point and relativised to the performance score of the non-injured leg at pre-surgery and at 24 weeks post-surgery, were used to compute correlation coefficients (Pearson product-moment) amongst outcome variables of IKDC, single-leg hop, anterior tibio-
Secondly, relationships amongst subjective and objective outcome measures of function, and outcomes of musculoskeletal and neuromuscular performance associated with changes in absolute scores for the injured leg from pre-surgery to 24 weeks were assessed as follows: The potential for relationships associated with the rehabilitation-related patterns of change amongst outcome variables was assessed by computing correlations (Pearson product-moment) involving the difference score for each outcome between pre-surgery and at 24 weeks post-surgery, with relativisation to the performance score of the non-injured leg at pre-surgery, where appropriate (i.e. in those indices offering data for each leg).

* A priori alpha levels were set at *p*<0.05. Two-tailed probabilities were used due to the exploratory nature of this study and potential for both differing timing of performance and functions losses and gains amongst the outcomes over the follow-up period (Gleeson et al., 2008).

6.4 Results

The manipulation-checks and confirmation for statistically-significant changes over time (pre-surgery and at 24 weeks post-surgery) in group mean scores of subjective (IKDC) and objective (HOP) outcome measures of function and objectively-measured musculoskeletal and neuromuscular performance outcomes of anterior tibio-femoral displacement (ATFD), peak force (PF, ext. & flex.), rate of force development (RFD, ext. & flex.), electromechanical delay (EMD, ext. & flex.), force error (FE, ext. & flex.), are presented within this thesis (Chapters 4 and 5). Results for all outcomes showed statistically-significant
and clinically-relevant functional and performance improvements over time in patients undergoing both non-concurrent NCON (n=33 [7 lost to follow-up]) or traditional concurrent rehabilitation CON (n=31 [9 lost to follow-up]). The extent of an interaction and improvement was dependent on the mode of rehabilitation conditioning ($F_{(2.1, 131.6)} \geq 4.5; p<0.01$). However, the inter-group differences in capability were small to moderate in absolute effect (~5% - 15%) and not considered sufficient, relative to the population heterogeneity of response in general, to preclude the useful amalgamation of the results of assessments of the population of patients undergoing ACL-reconstruction surgery in this study. Amalgamation (‘pooling’) of data would be expected to offer greater statistical robustness that might better identify possible relationships amongst the outcomes in this exploratory study.

6.4.1 Relationships amongst subjectively-measured function and objectively-measured outcomes of function, musculoskeletal and neuromuscular performance associated with absolute scores for the injured leg

Relationships between the subjective outcome of function (IKDC) and the objective outcome measure of function (HOP) and between IKDC and objective outcome measures of musculoskeletal performance, anterior tibio-femoral displacement (ATFD) and neuromuscular performance, peak force (PF, ext. & flex.), rate of force development (RFD, ext. & flex.), electromechanical delay (EMD, ext. & flex.) and force error (FE, ext. & flex.), associated with the absolute scores of the injured leg, where appropriate, at assessment points of pre-surgery and 24 week follow-up, are shown in Tables 6.1 and 6.2.
Table 6.1  Relationship between the subjectively-measured function (IKDC) and the objectively-measured outcomes of function, musculoskeletal and neuromuscular performance at pre-surgery – absolute scores – injured limb.

<table>
<thead>
<tr>
<th>Pre-surgery</th>
<th>HOP</th>
<th>ATFD</th>
<th>PF</th>
<th>RFD</th>
<th>EMD</th>
<th>FE</th>
</tr>
</thead>
<tbody>
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<td></td>
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<tr>
<td>ext</td>
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<td>ext</td>
<td>flex</td>
<td>ext</td>
<td>flex</td>
<td>ext</td>
</tr>
<tr>
<td>IKDC</td>
<td>-.019</td>
<td>.069</td>
<td>.178</td>
<td>.220</td>
<td>.402†</td>
<td>.404‡</td>
</tr>
<tr>
<td>Pearson Correlation (Sig. 2-tailed)</td>
<td>(.879)</td>
<td>(.588)</td>
<td>(.158)</td>
<td>(.080)</td>
<td>(.001)</td>
<td>(.001)</td>
</tr>
</tbody>
</table>

Notes: † Significant correlation (p<0.05); ‡ Significant correlation (p<0.01) (n=48).

Table 6.2  Relationship between the subjectively-measured function (IKDC) and the objectively-measured outcomes of function, musculoskeletal and neuromuscular performance at 24 weeks post-surgery – absolute scores – injured limb.

<table>
<thead>
<tr>
<th>24 weeks post-surgery</th>
<th>HOP</th>
<th>ATFD</th>
<th>PF</th>
<th>RFD</th>
<th>EMD</th>
<th>FE</th>
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<tbody>
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<td></td>
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<tr>
<td>ext</td>
<td>flex</td>
<td>ext</td>
<td>flex</td>
<td>ext</td>
<td>flex</td>
<td>ext</td>
</tr>
<tr>
<td>IKDC</td>
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<td>.153</td>
<td>.283</td>
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<td>.038</td>
</tr>
<tr>
<td>Pearson Correlation (Sig. 2-tailed)</td>
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<td>(.803)</td>
<td>(.226)</td>
<td>(.023)</td>
<td>(.831)</td>
<td>(.765)</td>
</tr>
</tbody>
</table>

Notes: † Significant correlation (p<0.05); ‡ Significant correlation (p<0.01) (n=48).

6.4.2 Relationships amongst subjectively-measured function and objectively-measured outcomes of function, musculoskeletal and neuromuscular performance associated with injured-contralateral leg differences

Relationships involving injured-contralateral limb differences (where appropriate, and relativised to the performance of the non-injured leg at pre-surgery) between the subjective outcome of function (IKDC) and the objective
outcome measure of function (HOP) and between IKDC and objective outcome measures of musculoskeletal performance, anterior tibio-femoral displacement (ATFD) and neuromuscular performance, peak force (PF, ext. & flex.), rate of force development (RFD, ext. & flex.), electromechanical delay (EMD, ext. & flex.) and force error (FE, ext. & flex.), at pre-surgery and at the 24 weeks follow-up point of assessment, are shown in Tables 6.3 and 6.4, respectively.

### Table 6.3  Relationships between the subjectively-measured function (IKDC) and the objectively-measured outcomes of function, musculoskeletal and neuromuscular performance associated with the injured versus non-injured (contralateral) leg differences at pre-surgery.

<table>
<thead>
<tr>
<th></th>
<th>Pre-surgery</th>
<th>HOP</th>
<th>ATFD</th>
<th>PF</th>
<th>RFD</th>
<th>EMD</th>
<th>FE</th>
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<tr>
<td></td>
<td></td>
<td>ext</td>
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<td>ext</td>
<td>flex</td>
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<td>flex</td>
</tr>
<tr>
<td>IKDC</td>
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<tr>
<td>Pearson Correlation (Sig. 2-tailed)</td>
<td>† Significant correlation (p&lt;0.05); ‡ Significant correlation (p&lt;0.01) (n=48).</td>
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</tr>
<tr>
<td>HOP</td>
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<tr>
<td>PF</td>
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<td>-.235</td>
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</tr>
<tr>
<td>RFD</td>
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</tr>
<tr>
<td>EMD</td>
<td>.095</td>
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<td></td>
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<tr>
<td>FE</td>
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</tbody>
</table>

### Table 6.4  Relationships between the subjectively-measured function (IKDC) and the objectively-measured outcomes of function, musculoskeletal and neuromuscular performance associated with the injured versus non-injured (contralateral) leg differences at 24 weeks post-surgery.

<table>
<thead>
<tr>
<th></th>
<th>24 weeks post-surgery</th>
<th>HOP</th>
<th>ATFD</th>
<th>PF</th>
<th>RFD</th>
<th>EMD</th>
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<tr>
<td>Pearson Correlation (Sig. 2-tailed)</td>
<td>† Significant correlation (p&lt;0.05); ‡ Significant correlation (p&lt;0.01) (n=48).</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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</tr>
<tr>
<td>RFD</td>
<td>.313†</td>
<td>.379‡</td>
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</tr>
<tr>
<td>EMD</td>
<td>.002</td>
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<td></td>
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</tbody>
</table>

Notes: † Significant correlation (p<0.05); ‡ Significant correlation (p<0.01) (n=48).
6.4.3 Relationships amongst subjectively-measured function and objectively-measured outcomes of function, musculoskeletal and neuromuscular performance associated with pattern of change for the injured leg over the period of rehabilitation

Relationships between the pattern of change in the subjective outcome of function (IKDC) and the objective outcome measure of function (HOP) and between IKDC and objective outcome measures of musculoskeletal performance, anterior tibio-femoral displacement (ATFD) and neuromuscular performance, peak force (PF, ext. & flex.), rate of force development (RFD, ext. & flex.), electromechanical delay (EMD, ext. & flex.) and force error (FE, ext. & flex.), between pre-surgery and 24 weeks post-surgery, are shown in Table 6.5.

<table>
<thead>
<tr>
<th>Pattern of change between pre-surgery and 24 weeks post-surgery</th>
<th>HOP</th>
<th>ATFD</th>
<th>PF</th>
<th>RFD</th>
<th>EMD</th>
<th>FE</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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<td>IKDC</td>
<td>0.31†</td>
<td>-0.07</td>
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<td>0.242</td>
<td>0.212</td>
<td>0.228</td>
</tr>
<tr>
<td>Pearson Correlation (Sig. 2-tailed)</td>
<td>(.047)</td>
<td>(.957)</td>
<td>(.559)</td>
<td>(.058)</td>
<td>(.098)</td>
<td>(.074)</td>
</tr>
</tbody>
</table>

Notes: † Significant correlation ($p<0.05$); ‡ Significant correlation ($p<0.01$) (n=48).
6.5 Discussion

The aim of this study was to explore the relationships amongst a subjective (self-perceived) measure of knee function (International Knee Documentation Committee [IKDC] knee evaluation form, a primary outcome measure of the thesis) and objectively-measured outcomes of function (single-leg hop for distance [HOP]), musculoskeletal performance (anterior tibio-femoral displacement [ATFD; knee laxity]), and neuromuscular performance (peak force [PF, strength], rate of force development [RFD], electromechanical delay [EMD]), force-error [FE]), at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery. Where applicable, the measures were associated with the knee extensors and flexors of the injured and non-injured legs in a population who had undergone ACL reconstructive surgery and subsequent rehabilitation. These relationships were evaluated in order to determine if significant statistical and/or clinically-relevant correlations existed. Anterior tibio-femoral displacement (ATFD), peak force (PF), rate of force development (RFD), electromechanical delay (EMD), and sensorimotor performance (SMP) are common tools of assessment following injury and surgery to knees (Gleeson et al. 1996, 1998, 2005, 2008, Minshull et al. 2007, 2009, 2011). In particular, hop testing is frequently used in clinical practice as a performance-based outcome measure related to functional capacity (Fitzgerald 2000, Clark 2001, Hopper et al. 2002, Gustvasson et al. 2006, Reid et al. 2007, Thomeé et al. 2011). It reflects knee joint dynamic stability by integrating the effects of neuromuscular control, strength and self-perceived confidence in the limb (Fitzgerald et al. 2001, Reid et al. 2007). Additionally, it requires no costly testing equipment and minimal practitioner time to administer.
This correlation study found a limited, but statistically significant relationship between the subjective and objective functional outcomes, IKDC and HOP, associated with the injured versus non-injured (contralateral) leg differences, at both the pre-operative and 24 weeks post-operative assessment occasions \((r = -0.331; p < 0.05\) and \(r = -0.258; p < 0.01\), respectively). This suggested that the relationship between these two measures show some statistical significance but that it has no meaningful clinical relevance and that both the IKDC and HOP are essentially independent parameters contributing to the description of patients’ functionality. In addition, the parity of correlation at pre-surgery and 24 weeks post-surgery showed that the robustness of the correlation does not appear to have been influenced by the rehabilitation conditioning over the initial 24 weeks of the programme of care.

This finding is similar to the weak statistical significance reported in a review comparing subjective outcome scores with objective measures by Fitzgerald (2001). However, it is possible that the relationship between HOP and IKDC would exhibit an increased robustness of correlation over a longer post-surgical time-frame. A research study by Reinke et al. (2011) compared four types of hop tests with current versions of patient subjective inventories (including IKDC) in ACL-reconstructed patients. The patients were tested prior to surgery and between 2.2-3.2 years following surgery. The study found a moderate, but significant, correlation between single hop and IKDC (Spearman correlation: \(\rho = 0.3; p < 0.005; R^2 = 0.2\)). However, while there is some weak to moderate statistical significance found in both the correlations analysed as part of this thesis and in the study by Reinke at al. (2011), these findings offer no evidence for either approach to be used clinically in isolation.
A prospective study by Risberg et al. (1999), evaluated the sensitivity changes over time for IKDC and found it to be a poor predictor of clinical changes due to its poor sensitivity. Nevertheless, the study also showed the IKDC as high criterion validity and worthy of documentation after ACL surgery. This finding also echoes the results presented in this chapter: IKDC at pre-surgery and 24 weeks post-surgery did show some statistically significant correlations with the secondary outcomes, for example IKDC and RFD absolute scores of the injured limb (knee extension and flexion) pre-operatively ($r = 0.402; p = 0.01$ and $r = 0.404; p = 0.01$, respectively); IKDC and EMD absolute scores of the injured limb (knee extensors and flexors) pre-operatively ($r = 0.402; p = 0.01$ and $r = 0.404; p = 0.01$, respectively); IKDC and EMD absolute scores of the injured limb (knee extensors and flexors) at 24 weeks ($r = -0.296; p = 0.05$ and $r = -0.321; p = 0.01$, respectively); IKDC and EMD injured versus non-injured limb differences (knee extensors and flexors) at 24 weeks ($r = 0.313; p = 0.05$ and $r = 0.379; p = 0.01$, respectively); IKDC and EMD pattern of change (knee extensors and flexors) from pre-surgery to 24 weeks post-surgery ($r = -0.304; p = 0.05$ and $r = -0.267; p = 0.05$, respectively). However, the strength of these correlations would not be sufficient for meaningful use in clinical practice and in the prediction of an individual patient’s functional capacity from physical capability, for example (coefficient of determination $[r^2]$ suggesting that less than 16% of the shared variance between outcomes might be explained). Across all the correlations, although some statistical significance is demonstrated, there are no relationships amongst the subjective and objective indices that would suggest any clinical relevance exists.

Furthermore, subjective functional capacity (IKDC) was not related strongly to candidate determinants such as musculoskeletal and
neuromuscular performance outcomes. Thus, the results suggest that it might be imprudent to attempt to use the relationships between the subjective knee evaluation (IKDC) and the secondary outcomes of musculoskeletal and neuromuscular performance in this thesis for the prediction of the former. The results mitigate against attempting to elucidate the possible correlates and determinants of subjective and objective functional outcome measures for the purpose of reviewing the optimal components of post-surgical rehabilitation. Similar findings have been observed in the literature (Sernert et al. 1999, Fitzgerald et al. 2001, Reid 2007, Park et al. 2010).

Importantly, these findings of weak to moderate correlations might give credence to a mis-matching of patients’ perception of functional capabilities and the true extent of their objective neuromuscular performance capacities. If the patient’s perception is that he/ she is better than his/ her musculoskeletal and neuromuscular capabilities, then this would suggest that this potentially could increase the risk of further injury if the patient chose to undertake activities that he/ she was not properly prepared for. Conversely, if the patient doesn’t feel capable, possibly due to fear (Heijne et al. 2007, Brewer at al. 2007, Webster et al. 2008, Ardern et al. 2012), then it might result in the patient’s sub-optimal efforts in rehabilitation.

In summary, while some statistically significant correlations exist between IKDC and HOP and between IKDC and the secondary objective outcomes of musculoskeletal and neuromuscular performance, the correlations should neither be considered sufficiently robust to offer clinical relevance nor be considered as isolated determinants of functional performance. The absence of a strong linkage amongst self-perceived (subjective) and objective indices of function and fitness performance suggested that both measurement
approaches to assessing function and the individual indices in themselves (given sufficient clinimetric qualities), might be contributing separate, but potentially important, aspects to the description of functional capacity. The results from this study supports the notion that current practice when evaluating post-surgical ACL reconstructive outcomes, should continue to use a battery of subjective and objective outcome measures of function alongside musculoskeletal and neuromuscular outcomes, in order to establish a comprehensive description of the performance, confidence and dynamic stability capabilities associated with the ACL-injured and surgically-reconstructed knee.

6.6 Conclusion

The complexities and multi-faceted needs associated with rehabilitation conditioning for the patient undergoing ACL-reconstruction surgery, are considerable. The conclusion of the findings of this study are congruent with latter complexities as in order to properly assess the effectiveness of rehabilitation on function and physical performance, none of the selected indices could be made redundant: Each would seem to be contributing separate and important facets to the description of functional, musculoskeletal and neuromuscular capacity status. Importantly, the subjective functional (IKDC) score cannot confidently predict objectively-measured outcomes of function, musculoskeletal or neuromuscular performance to a level required for clinical practice.
Chapter 7:

General Discussion and Conclusion of the Thesis
Chapter 7: General Discussion and Conclusion

7.1 Summary

The primary aim of this thesis was to assess via a randomised control trial, the effects of reconstruction surgery and 24 weeks of non-concurrent (NCON) strength and endurance rehabilitation (with 48 week post-operative follow-up) on self-perceived outcomes, objectively-measured outcomes of function, musculoskeletal performance and neuromuscular performance associated with anterior cruciate deficient knees. In addition, the possibility of clinico-social approbation brought about by increased assessor-patient interaction was examined. This thesis represents an exploratory study and novel attempt to assess the influence of a relatively simple manipulation of physiological exercise stress that might offer important gains in the environment of rehabilitative care within the NHS. Considerable attempts were made to ensure iso-volumetric rehabilitation dosage (with self-report verification of dosage) amongst the two main arms of the study (NCON and CON). This helped to ensure that any beneficial changes associated with NCON might properly be attributed to the altered patterning of the delivery of conditioning, rather than to poorly controlled volumetric differences amongst conditioning interventions. Importantly, it used the performance of the contralateral limb as a main control condition. Although some physiological de-conditioning of this control leg’s capabilities was likely to have occurred, due to altered physiological loading in the period between injury and surgery, it nevertheless represented a best estimate of a reference (baseline) performance capability (Gleeson et al. 2008).
Despite being at the level of an exploratory study, this thesis employed an experimental design involving a prospective trial with random-allocation to groups. In addition, an extra control group was deployed as a manipulation-check that patient’ clinico-social approbation had not intruded and that any relative gains in performance compared to current practice might be attributed properly to non-concurrent conditioning (refer to Chapter 3 – Section 3.2.5). While offering additional robustness to the experimental design and although maintaining minimally acceptable levels of power and potential for the intrusion of Type-II error and associated mis-interpretation of findings, this approach lost some design sensitivity, with fewer numbers of patients being available and meeting inclusion criteria than had been expected being allocated to the main arms of the trial.

The overall background and context to this thesis is explained in the literature review (Chapter 2). The anatomy of the anterior cruciate ligament (ACL) is described and the mechanisms of injury, the associated compromise to function, and the possible likelihood of further injury are examined. Thus, an ACL-injured population was chosen for this study as this type of injury is relatively commonplace and requires a minimum of 6 month rehabilitation with commensurate cost-implications to the patient, NHS and society (van Grinsven et al 2010, Manske et al. 2012, Lobb et al 2012). Traditionally, ACL rehabilitation is administered in a concurrent format (CON), whereby strength and cardio-vascular exercises are administered in close proximity. Concurrent rehabilitation (CON) is routinely prescribed despite evidence in healthy populations this type of training may attenuate strength gains (van Grinsven et al 2010, Manske et al. 2012, Lobb et al 2012, Wilson 2012). The compromise in strength gains have been attributed to an ‘interference effect’, brought about
by CON training (Doherty and Sporer 2000, Wilson 2012). Many authors have made suggestions regarding the cause of this effect, but no consensus currently exists (Doherty and Sporer 2000, Wilson 2012). The thesis’ literature review concludes that although standard ACL rehabilitation is efficacious, there might be a potential to improve outcomes by manipulating the sequencing of conditioning within the traditional CON rehabilitative practice by performing the same exercises in a non-concurrent (NCON) format.

Self-perceived (subjective) outcome measures of function are good indicators to how a patient rates his/ her deterioration or improvement, and/ or identifies problems that he/ she may be experiencing (Revicki et al. 2008). The International Knee Documentation Committee (IKDC) subjective knee evaluation form and the Knee Injury and Osteoarthritis Outcome Score (KOOS) were decided upon as they are commonly used inventories. Both possess appropriate clinimetric qualities to assess the outcome of ACL surgery and show similar, if not better, reliability in assessing ACL populations compared to other subjective measures (Herrald et al. 2006, Biau 2007, Higgins et al. 2007, Hambly 2010, Collins et al. 2011, Irrgang et al. 2012). The performance profile (PP) technique was decided upon, due to its bespoke and individualised nature in addressing patients’ concerns (Chapter 2 – Sections 2.5.1 – 2.5.3).

As the return to normal function is always the main aim of any rehabilitation programme, hop for distance (HOP) was selected as the objectively-measured primary outcome. This outcome is commonly used in clinical practice, and based on the amount of space available for assessments and the reliability of this measure, it was deemed most appropriate in comparison to shuttle sprint or carioca, for example (Clarke 2001, Gustavsson et al. 2006).
The secondary objectively-measured outcomes chosen were anterior tibio femoral joint displacement (ATFD) as a measure of joint laxity and commonly associated with ACL deficiency; peak force (PF); rate of force development (RFD); electromechanical delay (EMD) and sensorimotor performance (SMP measured by force error [FE]). These measures were determined based on their association with a proposed model of knee joint stability, normal function and injury prevention (Griffin et al. 2005, Blackburn et al. 2009), as discussed in Chapter 2 – Section 2.3.

Intention to treat was analysed for both the subjectively-measured and the objectively-measured outcome scores. Comparisons using ANOVA of group mean responses for outcomes at pre-surgery (baseline) amongst the Lost to follow-up (n=19), CON (n=22) and NCON (n=26) groups showed no significant differences. The only exception to this finding was for PF associated with the knee flexors (3.2% and 2.4% lower scores for Lost to follow-up injured and non-injured legs respectively \( [F(3.0, 97.0)_{GG} = 3.9; \ p<0.05] \)). This suggests that biasing of the data might have intruded in only a minor way and that the results are likely to be representative of the local and possibly wider patient populations.

In addition, the relationships between subjective (self-perceived) function and a selected range of indices; objective function (HOP), musculoskeletal and neuromuscular performance (ATFD, PF, RFD, EMD and SMP) were evaluated. If strong relationships were to have been found amongst the candidate outcome measures, then it could have led to a reduction in the size of the battery of objective measures required in the future to assess musculoskeletal and neuromuscular performance and improvements in functional capability.
Therefore, the aims of this thesis were:

- To assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on self-perceived (subjective) measures of function (IKDC, KOOS, PP), in patients with anterior cruciate ligament deficiency (Chapter 4).

- To assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on HOP as an objective measure of function, in patients with anterior cruciate ligament deficiency (Chapter 5).

- To assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on objective measures of musculoskeletal (ATFD) and neuromuscular performance (PF, EMD, RFD, SMP), in patients with anterior cruciate ligament deficiency (Chapter 5).

- To explore the relationships amongst subjective (self-perceived) measure of knee function (International Knee Documentation Committee [IKDC] knee evaluation form, a primary outcome measure of the thesis) and objective measures of function (single-leg hop for distance [HOP]), musculoskeletal (anterior tibio-femoral displacement [ATFD; knee laxity]) and neuromuscular performance (peak force [PF, strength], rate of force development [RFD], electromechanical delay [EMD]), force-error [FE]), at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery (Chapter 6).
The purpose of this chapter is to discuss and contextualise the results of the RCT addressed in Chapters 4 and 5 and what these might imply clinically. The correlations of selected indices (Chapter 6) are discussed to give a possible insight into relationships between subjective (self-perceived) and objective outcome measures. The limitations of this study are addressed alongside recommendations for future research projects. Ultimately, this chapter provides a suggestion for the transformation of ACL rehabilitative practice. Table 7.1 presents the thesis questions raised in Chapter 1 – Section 1.4, and the key findings following the investigations reported in Chapters 4, 5 and 6, and thus provides a brief thesis’ summary.
### Thesis Question

**i) Is there evidence that NCON rehabilitation improves self-perceived functional responses as measured by IKDC, KOOS and PP following ACL rehabilitation compared to traditional CON practice?**

**Key Findings**

- Both NCON and CON demonstrated improved outcomes. However, NCON was superior.
- IKDC and KOOS demonstrated the most significant overall interaction at 12 weeks post-surgery.
- PP demonstrated the most significant overall interaction at 24 weeks post-surgery.
- NCON showed improvements in IKDC group peak relative difference of 10.8% at 12 weeks and 8.5% at 48 weeks compared to CON.
- NCON showed improvements in KOOS group peak relative difference of 10.6% at 12 weeks and 5.9% at 48 weeks compared to CON.
- NCON showed improvements in group PP peak relative difference of 12.7% at 24 weeks and 6.2% at 48 weeks compared to CON.

**ii) Is there evidence that NCON rehabilitation improves objectively-measured outcomes of functional, musculoskeletal and neuromuscular performance following ACL rehabilitation compared to traditional CON practice?**

**Key Findings**

- Beneficial gains were seen in all the objective measures in both groups for both limbs over the rehabilitation period.
- The NCON group out-performed the CON group in every outcome (with the exception of SMP for knee flexors).
- The percentage advantage of NCON rehabilitation versus CON at the 48 weeks assessment stage is outline in below:

<table>
<thead>
<tr>
<th>48 weeks assessment</th>
<th>NCON % advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOP</td>
<td>6.3**</td>
</tr>
<tr>
<td>ATFD</td>
<td>14.2***</td>
</tr>
<tr>
<td>Ext</td>
<td>5.9*</td>
</tr>
<tr>
<td>Flex</td>
<td>15.3*</td>
</tr>
<tr>
<td>PF</td>
<td>5.4*</td>
</tr>
<tr>
<td>RFD</td>
<td>7.9*</td>
</tr>
<tr>
<td>EMD</td>
<td>9.3*</td>
</tr>
<tr>
<td>RFD</td>
<td>11.9***</td>
</tr>
<tr>
<td>SMP</td>
<td>5.6**</td>
</tr>
<tr>
<td>SMP</td>
<td>4.7**</td>
</tr>
</tbody>
</table>

* = (p<0.05) ** = (p<0.01) *** = (p<0.005)

- The most significant interactions were found to occur at 12 and 48 weeks post-operatively.

**iii) Are there relationships amongst the subjective measure of knee function (IKDC) and objective measures of function (HOP), musculoskeletal (ATFD) and neuromuscular (PF, RFD, EMD and SMP) performance at pre-surgery and 24 weeks post-surgery and amongst the change score between pre-surgery and 24 weeks post ACL reconstructive surgery?**

**Key Findings**

- Limited statistical correlations were found between IKDC and HOP (injured leg versus non-injured [contralateral] leg difference) at pre-surgery and 24 weeks post-surgery (range $r = -0.331 \text{ to } -0.310 \text{ p<0.05}$).
- Limited statistical correlations were found between IKDC and RFD and EMD (range $r = 0.266 \text{ to } 0.404 \text{ p<0.05}$).
- No relationship was found to be clinically relevant.
- IKDC is independent to all objective outcomes in a clinical scenario.

### Table 7.1 Research questions and key findings.
7.2 Is there evidence that NCON rehabilitation improves self-perceived functional responses following ACL reconstruction compared to traditional CON practice?

Patient reported, self-perceived or subjective are interchangeable terms commonly used to describe outcomes that measure how the patient feels an intervention has affected them (Copay et al. 2007, Revicki et al. 2008). The self-perceived (subjective) outcome measures of function used in this thesis were International Knee Documentation Committee (IKDC) subjective knee evaluation form, the Knee injury and Osteoarthritis Outcome Score (KOOS), and the Performance Profile (PP). There appears to be no universally-accepted ‘gold’ standard assessment tools in this respect (please see the Chapter 2 – Sections – 2.5.1 to 2.5.3) and so an array of outcomes were selected on popularity of use and clinimetric quality.

The following sections, 7.2.1 – 7.2.3 relate to the thesis aim, “To assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on self-perceived (subjective) measures of function (IKDC, KOOS, PP), in patients with anterior cruciate ligament deficiency.” Section 7.2.4 discusses evidence of clinico-social approbation with respect to the self-perceived findings.

7.2.1 Is there evidence that NCON rehabilitation improves functional responses as measured by IKDC, following ACL reconstruction compared to traditional CON practice?

The IKDC score is a commonly used score when assessing patients following ACL injury and surgery (Herrald et al. 2006, Biau et al. 2007, Higgins et al. 2007, Hamby 2010, van Grinsven et al. 2010, Collins et al. 2011, Irrgang
et al. 2012). It has been reported to offer adequate internal consistency for mixed sex groups with various knee pathologies (Collins et al. 2011). As discussed in Chapter 2 - Section 2.5.1, the IKDC test-retest reliability has been shown to be 0.87 – 0.98 respectively (Collins et al. 2011, Irrgang et al. 2012), and the effect size and standardised response to mean, range from 0.76 – 2.11 and 0.57 – 1.5, respectively (Irrgang et al. 2012).

The results from the random controlled trial presented in Chapter 4 - Section 5.4.1, showed that improvements were gained in both the NCON and traditional CON groups. This provided comforting evidence that both the surgery and progressive rehabilitation improves the patient's view of his/her function, irrespective of the group to which they had been randomly allocated. However, the group mean scores associated with NCON were superior ($F_{(2, 131.6)} = 4.5; p<0.01$) over the 48 weeks assessment period.

Over the duration of the study the 6 weeks assessment point shows deterioration in the IKDC score, but less so in the NCON group compared to the CON group. This pattern of response was also found in the KOOS and PP inventories, and was most likely associated with the insult of the ACL surgery together with arthrogenic and rehabilitative restrictions the patient will have experienced in the first post-operative 6 weeks (Table 7.2).

The largest significant component of overall interaction and difference between NCON and CON groups, was seen at 12 weeks post-surgery compared to previous assessments at 6 weeks post-surgery and pre-surgery as outlined in Table 7.2.
### Table 7.2  Summary of IKDC score improvement following NCON versus CON ACL rehabilitation at pre-surgery, 6 weeks and 12 weeks post-surgery.

The improvement in the IKDC score of 6 units when comparing NCON to CON rehabilitation at 12 weeks post-surgery is not only statistically significant, but it might also be clinically significant. The peak advantage of NCON over CON was 10.8% at 12 weeks post-surgery and this amount of self-perceived improvement is achievable with no extra burden to the patient, clinician or institute. The advantage might be sufficient to suggest a transformation of CON to NCON rehabilitation. However, minimal detectable change and minimal important clinical difference have been shown to vary in the literature (6.7 – 20.5 [MDC] and 3.19 – 16.7 [MCID]), which makes it difficult for a firm conclusion to be made about the robustness of the latter interpretation (Collins et al. 2011, Irrgang et al. 2012). Nevertheless, this amount of improvement might imply clinical significance.

Clinically, it could be speculated that greater improvements in IKDC scores are seen at 12 weeks, because it takes approximately 6 weeks for a patient to recover from the insult of surgery (van Grinsven et al. 2010). From 6 to 12 weeks, patients will have resumed the majority of activities of daily living, including commencement of more structured strengthening and cardio-vascular
endurance work [Appendix A - RJAH anterior cruciate ligament rehabilitation guide] and this might be reflected in the IKDC score.

With respect to the healing of the graft tissue, at 6 weeks ACL post-surgery Sharpey’s fibres (Type I collagen) are present within the bone tunnel (Oryan et al. 2013). These fibres have been used as a marker of healing and integration between the graft tissue and the bone tunnels where they have been sited (Fu et al. 1999, Oryan et al. 2013). This shift in healing might give rise to the sensation of the knee ‘feeling’ more stable by the 12 week test occasion, and could be a reason for why the patient might feel that he/ she has improved function. It should be remembered that the effects of healing would have been present in both the NCON and CON groups, and so this discussion does not fully answer why NCON patients perceived greater function compared to the CON. It could be speculated that the greater gains established by NCON rehabilitation might be due to the patient’s superior increases in musculoskeletal and or neuromuscular performance relative to the CON group, thus allowing them to increase his/ her actual and perceived functional capabilities.

From the 12 weeks assessment occasion, both groups continue to improve, with NCON rehabilitation maintaining superior outcomes compared to traditional CON practice at both 24 weeks and 48 weeks post-operatively. However by 48 weeks, the group mean relative difference in improvement in IKDC scores in the NCON group versus CON group was 8.5%, and less than the 10.8% difference found at 12 weeks.

Interestingly, the time point at which the most significant interaction occurred differs from the results reported in previous literature. Risberg et al. (1999) found the most significant change in IKDC scores following ACL reconstructive surgery occurred at 6 months. This latter result is in agreement
with the Collins et al. (2011), where the largest effect sizes were also found to occur from 6-months post ACL surgery. This variation of when the most significant improvements in IKDC occurred, might be a reflection on how the patients were rehabilitated overall. Unfortunately, the rehabilitative ACL regimens were not documented by Risberg et al. (1999) or Collins et al. (2011), precluding meaningful clinical comparisons and rendering these points as speculation.

As noted earlier, the group mean peak relative difference in improvement in IKDC scores in the NCON group versus CON group was 10.8% at 12 weeks post-surgery and 8.5% at 48 weeks post-surgery. Possibly, this might be due to the inclusion of open kinetic chain quadriceps exercises, cycling outdoors, breaststroke leg kick, jogging progressing to running and agility type drills from 12 weeks onwards in both study groups. While necessarily influencing both groups these rehabilitation features might have lessened the perceptions of gains in functional capability offered by antecedent NCON conditioning, essentially equalising the perceptions of functional capability between groups to a greater extent. Similarly, from week 24 the supervised rehabilitation stops as patients return to their normal daily, recreational and sporting activities, potentially to differing degrees and greater emphasis on unstructured activities rather than on the systematic rehabilitative conditioning, might also have lessened the superior effect of NCON training.

In comparison with previous studies, the evidence based systematic review of ACL rehabilitation by van Grinsven et al. (2010) recommends utilising the IKDC scoring system pre-operatively and prior to returning to sports. Unfortunately, the authors do not give any indication of improvement criteria or the ideal score that should be achieved prior to returning to sport. However, an
evaluation of knee ligament injuries with the IKDC scoring system suggests that an IKDC score of 80 – 90% reflects normal to nearly normal function and that it is questionable whether the knee will ever be fully restored following ACL surgery (Hefti et al. 1993). This is similar to the recommendation of 85 – 90% as a functional ‘cut off’, defining a successful outcome presented by Lynch et al. (2013), and the normative data ranging from 86 – 89%, documented by Herrington (2013). If this recommendation is to be followed, neither the NCON or CON groups as advocated solely by the IKDC score, should have returned to sports at 24 weeks and at 48 weeks post-surgery, as even the CON group would still have been falling short of these criteria. However, based on the clinical judgement of the multi-disciplinary team caring for patients in this study, no restrictions after 24 weeks were placed on either group on returning to function.

In summary, both NCON and CON rehabilitation following ACL surgery improved subjective, patient-reported outcomes as measured by IKDC. However, patients that rehabilitated in a NCON format showed superior results throughout, most significantly at 12 weeks post-surgery.

7.2.2 Is there evidence that NCON rehabilitation improves functional responses as measured by KOOS, following ACL reconstruction compared to traditional CON practice?

The KOOS outcome measure like the IKDC score is knee specific and is used in ACL populations. However, it was devised to recognise arthritic symptoms predominantly (Comins et al. 2008). This is useful as it is established that patients who have undergone ACL injury and or surgery do have a higher risk of developing osteoarthritis (Lohmander et al. 2004). In
addition, both the IKDC and KOOS scores are recommended by the National Knee Ligament Registry (http://www.uknlr.co.uk/) (Hill and O’Leary 2013).

The literature review Chapter 2 - Section 2.5.2, reports the internal consistency, test-retest reliability, effect size, and minimal detectable change for each of the 5 dimensions measured in the KOOS. These are similar to those reported for IKDC scores, and show adequate internal consistency, reliability and validity (Collins et al. 2011). These are summarised in table 7.3.

<table>
<thead>
<tr>
<th></th>
<th>Symptoms</th>
<th>Pain</th>
<th>ADL</th>
<th>Sports</th>
<th>QOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal</td>
<td>α = 0.25 – 0.83</td>
<td>α = 0.65 – 0.94</td>
<td>α = 0.78 – 0.97</td>
<td>α = 0.84 – 0.98</td>
<td>α = 0.64 – 0.90</td>
</tr>
<tr>
<td>consistency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test-retest</td>
<td>R1 = 0.74 – 0.95</td>
<td>R1 = 0.80 – 0.92</td>
<td>R1 = 0.73 – 0.94</td>
<td>R1 = 0.45 – 0.89</td>
<td>R1 = 0.60 – 0.95</td>
</tr>
<tr>
<td>reliability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effect Size</td>
<td>0.72 – 1.63</td>
<td>0.82 – 2.59</td>
<td>0.67 – 2.25</td>
<td>0.90 – 1.31</td>
<td>1.15 – 2.8</td>
</tr>
<tr>
<td>Minimal Detectable</td>
<td>9.9 – 24.3</td>
<td>11.8 – 29.0</td>
<td>11.9 – 31.5</td>
<td>12.2 70.0</td>
<td>14.2 – 34.0</td>
</tr>
<tr>
<td>Change</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.3  Summary of the internal consistency, reliability and validity of the KOOS inventory (Collins et al. 2011) [Information as shown in Table 2.1 for ease of reference].

The results from the RCT investigating the benefits of NCON rehabilitation compared to the traditional CON (Chapter 4 - Section 5.4.2), showed superior results as measured by KOOS for NCON rehabilitation throughout the investigative period \( F_{(2, 134.7)} > 5.5; \; p<0.001 \). A priori analysis suggested most interaction occurred at the 12 week post-operative assessment occasion \( F_{(1, 60)} > 21.7; \; p<0.001 \).

All five of the KOOS domains maintained a similar order of ranking over the 48 week assessment period. For example, quality of life scored lowest pre-
operatively followed by sport, then symptoms, then pain, with activities of daily living scored the highest for both the CON and NCON groups. However, the exception were quality of life and sport and recreation scores, these overlapped from the 6 week test occasion.

The possible reason for this ranking is speculative. Pre-operatively, it would appear that if sport and recreation scored low, so did the quality of life. The score for sport and symptoms at this assessment point are similar. This possibly alludes to the possibility that ‘symptoms’ as defined by KOOS, are affecting the level of sport and recreation, and thus quality of life. Pain scored higher than symptoms pre-operatively, which would fit with an ACL injury: It is well known that patients complain predominantly of instability over pain.

At the six weeks post ACL reconstruction assessment period, with the exception of quality of life and symptoms, there is a decrease in the KOOS score. This can possibly be a reflection of the insult of the operative procedure and restrictions placed on physical tasks such as running and twisting and turning, etc.

By the 12 week assessment point, four of the domains show a significant improvement compared to the baseline scores. The only exception was sport and recreation. However, this is probably due to the post-operative activity restrictions, whereby ‘sporting’ type activities would not have been advised up to this point. However in general, the NCON group perceived better function than the CON group by at least 10.6%. This was similar to the IKDC result and the same speculative reasoning why the most significant improvement occurred at this time, might be applied.

The 12 week assessment point finds that patients in all groups showed improvements in all five domains compared to the pre-operative scores. This is
the time point from which no restrictions clinically are placed on patients with respect to sport and recreation.

By the final assessment point of 48 weeks, this improvement has continued and the NCON group once again maintained superior scores, perceiving 5.9% greater improvements compared to the CON group. This difference is less than at 12 weeks and it might be associated with the resumption of normal activities, whereby formal sequencing of strength and endurance exercise is no longer adhered to.

Interestingly, the KOOS outcome score demonstrated in this study at 48 weeks post-surgery appear better than those presented in a previous randomised control trial, comparing early with delayed ACL reconstruction (Frobell et al. 2010). However, Frobell et al. (2010) graphically amalgamates the KOOS subscales at this time point, so it is difficult to assess the exact difference. In addition, the KOOS results for each subscale for the NCON group in this thesis are similar to those found by Beynnon et al. (2005), where accelerated versus non-accelerated ACL rehabilitation had been investigated.

Roos and Lohmander (2003) suggest an 8 – 10 point change in a KOOS score might represent minimal perceptible clinical improvement following ACL reconstruction. Unfortunately, Irrgang (2012) disputes this and suggested that there are varied approaches determining minimal detectable change (MDC), and that the minimal clinically important difference (MCID) associated with the KOOS outcome score, has yet to be identified.

Upon completion of this thesis, no recommendation with respect to subscales score prior to returning to full sporting activity could be offered, although normative data is reported to range from 90 – 100 for pain, 84 – 96 for symptoms, 92 – 100 for daily function, 80 – 100 for quality of life and 80 – 100
for sports and recreation (Herrington 2013). Therefore, it might be reasonable to assume post-operative scores in these regions will allow a safe return to full function. In addition, until the patient returns to full function, they might not be able to score as highly as those participating in sport, for example.

In summary, both NCON and CON groups showed significant statistical and clinical improvements in all of the subscales measured by KOOS. Importantly, on the basis of the limits expected for the proper detection of systematic changes to an ‘individual’s’ performance (MDC) and whether this approach to rehabilitation conditioning might have ‘real-world’ application, the group mean scores for the NCON group exceeded this criteria in all the subscales.

7.2.3 Is there evidence that NCON rehabilitation improves functional responses as measured by the PP technique, following ACL reconstruction compared to traditional CON practice?

In contrast to IKDC and KOOS, the performance profile (PP) does not have a set questions or statements for the patient to answer or rate, instead, the patient identifies what symptoms or differences to their ‘normal’ limb that are important to them, and rates them accordingly. The PP technique was included in the thesis as it offers a method of assessing the patient on an individual basis and it has been shown to promote compliance and task-motivation (Doyle et al. 1998). As discussed in Chapter 2 – Section 2.5.3, Doyle and Parfitt (1996) reported that the construct validity results showing that the items which the participant has determined as important, were the most sensitive to change. However, the authors do recommend caution, as the PP is unlikely to identify
relatively small changes in performance and perceived need. Nevertheless, this limited ability to detect small changes might not be as crucial in ACL injured or reconstructed patients, where large changes in performance are expected (Doyle et al. 1998).

The random control trial outlined in Chapter 4 – Section 4.4.3, reports a 2-way ANOVA using factors of group by test occasion (pre-surgery and 6, 12, 24 and 48 weeks post-surgery) with repeated measures on the latter, showed improvements in both NCON and CON groups. However, the NCON group reported superior results ($F_{(1.9, 121.4)}^{GG} = 14.6; p < 0.001$) over the 48 weeks assessment period.

Similarly to the findings for IKDC and KOOS, the PP score deteriorated at the 6 weeks assessment occasion compared to pre-operatively, and the same speculative reasoning involving the insult of surgery, and arthrogenic and rehabilitation restrictions, might be applied to account for this finding. However, from the 12 weeks assessment point, the PP shows an improvement compared to baseline, and especially in the NCON group.

Interestingly, the largest effect associated with the overall significant interaction brought about by the experimental intervention, was seen at 24 weeks post ACL surgery (Table 7.4) and not at 12 weeks, in contrast to IKDC and KOOS. In general, the group mean peak relative difference in improvement in PP scores in the NCON group versus CON group showed an advantage of 12.7% at 24 weeks post-surgery, favouring the NCON conditioning.
<table>
<thead>
<tr>
<th>Test Occasion</th>
<th>NCON</th>
<th>CON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-surgery</td>
<td>4.5 ± 1.6</td>
<td>4.7 ± 1.5</td>
</tr>
<tr>
<td>24 weeks post-surgery</td>
<td>5.5 ± 1.2</td>
<td>4.9 ± 1.4</td>
</tr>
</tbody>
</table>

\[ F_{(1,62)} > 4.4; p<0.05 \]

Group mean peak relative difference NCON versus CON at 24 weeks post-surgery 12.7%

Table 7.4 Summary of PP score improvement following NCON versus CON ACL rehabilitation at pre-surgery and 24 weeks post-surgery.

It is curious as to why it should be that unlike IKDC and KOOS inventories which showed the greatest improvements at 12 weeks post-surgery, PP would have shown the largest improvements in patient’s individualised outcome at 24 weeks. This might be due to the bespoke nature of this outcome, where only constructs deemed to be important to each individual patient were assessed. One might speculate that the items patients specifically included and rated against their perception of normal (contralateral limb) were more related to advanced function, which takes longer to achieve in the rehabilitation and healing process.

However, similarly to the IKDC and KOOS results, there is less of a difference between the two groups at 48 weeks. Nevertheless, NCON rehabilitation remained superior to traditional CON practice until the end of the period of monitoring. The group mean relative difference in improvement in PP scores in the NCON group versus CON group, showed an advantage of 6.2% at 48 weeks post-surgery in favour of the NCON group.

Once again, the decrease in the difference between the groups might be explained by patients from both groups resuming their normal lifestyle without supervised rehabilitation and stringent segregation of strength and cardio-
vascular exercise, with a commensurate reduction in the legacy advantage of NCON conditioning.

It is difficult to establish the extent of the significance of the clinical value of these improvements, as no previous studies have addressed this matter. However, advantages in outcomes of 12.7% and 6.2%, respectively at 24 and 48 weeks post ACL reconstruction in favour of NCON rehabilitation and at no extra cost to practice, means that it might be reasonable to assume that this does have a clinical value by improving patients’ satisfaction.

In summary, there is evidence that NCON rehabilitation gives superior results when compared to CON rehabilitation following ACL reconstruction surgery. The greatest interaction demonstrating this occurs at 24 weeks post-surgery. Table 7.5 summarises the key findings (from Chapter 4) associated with the self-perceived outcomes following either NCON or CON ACL rehabilitation.

<table>
<thead>
<tr>
<th>Thesis Question</th>
<th>Key Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>i) Is there evidence that NCON rehabilitation improves self-perceived functional responses as measured by IKDC, KOOS and PP following ACL rehabilitation compared to traditional CON practice?</strong></td>
<td><strong>[Chapter 4]</strong></td>
</tr>
<tr>
<td></td>
<td>• NCON and CON demonstrated improved outcomes.</td>
</tr>
<tr>
<td></td>
<td>• IKDC and KOOS demonstrated the most significant overall interaction at 12 weeks post-surgery.</td>
</tr>
<tr>
<td></td>
<td>• PP demonstrated the most significant overall interaction at 24 weeks post-surgery.</td>
</tr>
<tr>
<td></td>
<td>• NCON showed improvements in IKDC group peak relative difference of 10.8% at 12 weeks and 8.5% at 48 weeks compared to CON.</td>
</tr>
<tr>
<td></td>
<td>• NCON showed improvements in KOOS group peak relative difference of 10.6% at 12 weeks and 5.9% at 48 weeks compared to CON.</td>
</tr>
<tr>
<td></td>
<td>• NCON showed improvements in group PP peak relative difference of 12.7% at 24 weeks and 6.2% at 48 weeks compared to CON.</td>
</tr>
</tbody>
</table>

**Table 7.5** Summary of the key findings associated with the thesis aim, to assess the effects of reconstruction surgery and 24 weeks of NCON rehabilitation (with a 48 weeks post-operative follow-up) on self-perceived (subjective) function compared to traditional CON practice, in patients with anterior cruciate ligament deficiency.
7.2.4 Does clinical and/or social approbation associated with increased assessor-patient interactions influence self-perceived (subjective) function?

As described in the General Methods Chapter (Chapter 3 - Section 3.2.5), a control group was included in the randomised control trial to identify if an assessor-patient interaction existed, which might have biased the outcomes. This additional control group undertook the same traditional concurrent rehabilitation as the CON group; the only difference was a purposeful reduction in test occasions, and thus assessor contact. In order to limit the assessor-patient interaction, this group was only tested pre-surgery and 48 weeks post-surgery.

A 2-way ANOVA involving factors for group (limited assessor-patient CON and CON) by test occasion (pre-surgery versus 48 weeks post-surgery) with repeated measures on the last factor, was used to assess the extent of clinico-social approbation. The results reported in Chapter 4 - Section 4.5.1, showed no significant differences between the groups for the primary outcome measure of subjective function, IKDC ($F_{(2.0, 82.9)}^{GG} = 4.0; p<0.05$), and also for KOOS and PP ($F_{(1.6, 79.1)}^{GG} = 4.1 - 17.9; p<0.01$). This suggested that clinical and/or social approbation by patients had not contributed to the outcomes associated with IKDC, KOOS or PP scores and that the improvements in outcomes might be properly attributed to the surgery, healing, rehabilitation and intervention.

In summary, this extra control group acted as a quality assurance that the results of the randomised control trial, described in Chapter 4, were brought about by the surgery, healing, rehabilitation and the intervention, and not biased by the increased interaction with assessor during the assessment period.
7.3 Is there evidence that NCON rehabilitation improves objectively-measured functional performance following ACL reconstruction compared to traditional CON practice?

Restoration of function is always the main aim in rehabilitation and as such, assessment of function was chosen as the primary outcome(s) for this study. Function can be assessed subjectively via patient-reported scores and IKDC, KOOS and PP, as discussed previously in this chapter. However, objective functional outcomes are also important as these might address other factors. The assessment of hop for distance (HOP) is an objective measure of function that is often used following ACL reconstruction surgery to assess whether a patient can safely return to sport (Clark 2001, Gustavsson et al. 2006). This index of capability was chosen as the primary objectively-measured outcome of function for this thesis.

The following section (7.3.1) relates to the thesis aim, “To assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on HOP as an objective measure of function, in patients with anterior cruciate ligament deficiency.”
7.3.1 Is there evidence that NCON rehabilitation improves functional responses as measured by hop for distance (HOP), following ACL reconstruction compared to traditional CON practice?

Chapter 3 - Section 2.6.1 reviewed the various functional assessments used in clinical practice and hop for distance (HOP) was deemed to be the most applicable for this study. A hop test allows the assessor to measure differences between the injured and non-injured (contralateral) limb as it requires the patient to demonstrate adequate stability, flexibility, strength, rate of force development, power, proprioception, neuromuscular control, dynamic balance, agility and confidence, all of which are applicable to the injured and post-operative ACL patient (Clark 2001). While some authors suggest functional hop tests including hop for distance (HOP) are insensitive on ACL deficient populations, it is still commonly used in the clinical setting and HOP is the most frequently used assessment described in the literature (Fitzgerald et al. 2000, Clark 2001, Fitzgerald et al. 2001, Gustavsson et al. 2006, Thomeé et al. 2011). A systematic review by Clark (2001) found that the test-retest and intra-rater reliability for HOP to be acceptable by demonstrating the intra-class correlation coefficients to range between 0.89 – 0.97. This range of scores reflecting clinimetric quality, is similar to more recent findings by Gustavsson et al. (2006).

The influence of NCON versus CON on HOP outcomes was assessed using ANOVA with repeated measures and showed significant group (CON/ NCON) by leg (injured/ non-injured) by test occasion (pre-surgery, 12, 24 and 48 weeks post-surgery) interaction for HOP. Interestingly, the group mean scores for the NCON group were superior to CON for both legs, but more pronounced in the injured leg ($F_{(2.1, 133.0)} = 4.2; \ p<0.01$). Furthermore, a priori
difference testing of greater progressive increases in HOP associated with NCON versus CON were greatest at 12 weeks post-surgery and the findings are summarised in table 7.6.

<table>
<thead>
<tr>
<th>Test Occasion</th>
<th>NCON</th>
<th>CON</th>
<th>$F_{(1,62)} = 13.1; p&lt;0.005$</th>
<th>Group mean peak relative difference NCON versus CON at 12 weeks post-surgery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-surgery</td>
<td>96.1 ± 25.1</td>
<td>99.1 ± 24.2</td>
<td>12.2%</td>
<td></td>
</tr>
<tr>
<td>12 weeks post-surgery</td>
<td>103.7 ± 21.8</td>
<td>91.8 ± 21.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 7.6 Summary of HOP improvement following NCON versus CON ACL rehabilitation at pre-surgery and 12 weeks post-surgery.**

It is worthwhile to note that a HOP test prior to 12 weeks post-ACL reconstruction is contraindicated due to the risk of adversely affecting the healing process of the immature graft. The amount of arthrogenic inhibition present at this acute stage might have predisposed the patient to further injury (Clark 2001, Manske et al. 2012, Oryan et al 2013).

The bilateral improvement identified was most likely due to the holistic nature of the rehabilitation performed. Furthermore, it might be reasonable to assume that the non-injured leg suffered a degree of deconditioning prior to the pre-operative test occasion. Following a significant injury such as an ACL rupture, the patient will refrain from sporting activity due to a number of reasons. Initially this might be due to pain and swelling, then instability and/or fear of re-injury (Hopkins and Ingersoll 2000, Rice and McNair 2010, Ardern 2012). Therefore, the post-operative period of rehabilitation is likely to show bilateral improvements.
It could be speculated that the NCON sequencing of rehabilitation brings about beneficial neuromuscular changes required to perform a hop earlier within the rehabilitation and that this might be a reason why greater gains in HOP are reported.

The NCON group continued to out-perform the CON group at 48 weeks post-surgery, but less difference was found between the two groups. This is possibly due to both groups resuming normal levels of activity and are no longer subjected to a supervised rehabilitation format, as previously discussed.

In general, the group mean relative difference in HOP improvements associated with NCON versus CON was 12.2% of baseline at 12 weeks and 6.3% at 48 weeks, in favour of NCON rehabilitation.

However, it is suggested in the literature that limb symmetry should be ≥85% before full sporting activity is commenced (Clark 2001, Gustavsson et al. 2006). Therefore, using this recommended percent of parity as a yardstick, the HOP results from this study at 48 weeks post-surgery, showed that the limb symmetry for the NCON group was above this recommended threshold, and that the CON group was just below, as outlined in the table 7.7.

<table>
<thead>
<tr>
<th>Test occasion - 48 weeks post-surgery</th>
<th>NCON</th>
<th>CON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HOP (cm)</td>
<td></td>
</tr>
<tr>
<td>Injured</td>
<td>125 ±10</td>
<td>105 ±22</td>
</tr>
<tr>
<td>Non-Injured</td>
<td>145 ±18</td>
<td>140±26</td>
</tr>
<tr>
<td>Limb Symmetry (%)</td>
<td>≈86±15%</td>
<td>≈75±25%</td>
</tr>
</tbody>
</table>

| [Injured score ÷ Non-injured score x 100] |

Table 7.7  Limb symmetry comparison following NCON and CON ACL rehabilitation.
The clinical implication of such a finding would be that the post-operative ACL CON group are not at the recommended stage of conditioning status to return to full sporting activity based solely on hop for distance limb symmetry.

In summary, there is evidence to show NCON rehabilitation results in a superior functional outcome throughout the assessment period of 48 weeks as measured by HOP. The greatest intervention interaction favouring NCON conditioning, was seen at 12 weeks post-surgery.

7.4 Is there evidence that NCON rehabilitation improves musculoskeletal and neuromuscular outcomes of performance following ACL reconstruction compared to traditional CON practice?

Both the subjective (IKDC, KOOS, PP) and objective (HOP) primary outcomes in this thesis reflect functional capability. In addition, this thesis included outcome measures of musculoskeletal and neuromuscular performance which have been correlationally linked to dynamic joint stability and injury prevention; anterior tibio-femoral displacement (ATFD), peak force (PF), rate of force development (RFD), electromechanical delay (EMD) and sensorimotor performance (SMP) (Chapter 2 - Sections 2.6.2 to 2.6.6).

The following sections 7.4.1 – 7.4.4 address the thesis aim, “To assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on objective measures of musculoskeletal (ATFD) and neuromuscular performance (PF, EMD, RFD, SMP), in patients with anterior cruciate ligament deficiency.” In addition, section 7.4.5 discusses the potential of clinical or social approbation of
the increased assessor-patient interaction on the HOP, ATFD, PF, RFD, EMD and SMP.

7.4.1 Is there evidence that NCON rehabilitation improves musculoskeletal performance as measured by anterior tibio-femoral displacement (ATFD), following ACL reconstruction compared to traditional CON practice?

The primary role of the ACL is to restrain the anterior displacement of the tibia on the femur (Duthen et al. 2006). When the ACL is ruptured, this passive restraint is lost, increasing ATFD and contributing to pathological joint laxity and instability. This in turn, leads to loss of normal function and increases the likelihood of further injury (Renstrom et al. 2008).

The method used to measure the amount of ATFD in this thesis is described in Chapter 3 - Section 3.8.1. This method has been shown to have coefficient of variations ranging from 8.7 (±7.1)% - 5.8 (±4.9)% for non-injured knees and 3.6 (±3.2)% - 2.5 (±1.8)% for ACL deficient knees. And intra-class correlation coefficients with a standard error of measurement (95% confidence intervals) of 0.98, 15.8% – 10.6% for the non-injured and 0.99, 7.5% - 7.0% for ACL deficient knees (Gleeson et al. 1996). These results suggested that this method of measuring ATFD of the knee is very reliable and is capable of discriminating 0.2 mm differences or changes in laxity of an individual patient’s knee.

In addition, previous literature proposes a 3mm difference in tibial position could discriminate between patients who could cope with an ACL deficient knee and those who could not (Chielewski et al. 2005). This is the
same amount of ATFD that is suggested as a minimal clinically important difference (MCID) by Di Stasi et al. (2012).

The ATFD results from the RCT performed are reported in Chapter 5 – Section 5.4.2.1, where large post-operative improvements are seen in both groups due to the immediate passive stability gained from the reconstructive surgery. The results were generated using ANOVA with repeated measures and identified significant group (NCON; CON) by leg (injured; non-injured) by test occasion (pre-operatively and 6, 12, 24 and 48 weeks post-operatively) interaction for ATFD. Group mean scores for ATFD showed improvements in both groups, however, NCON provoked superior laxity for both the non-injured and injured knees, and this was more pronounced in the injured knee \(F(1.3, 79.8)_{GG} = 14.9; p<0.005\). The most significant effect contributing to the overall interaction, based on \textit{a priori} ‘difference’ testing of hypothesis for greater progressive decreases in ATFD associated with NCON versus CON rehabilitation, occurred at the 48 week test occasion. This finding is outlined in table 7.8.

<table>
<thead>
<tr>
<th>Test Occasion</th>
<th>Injured limb - ATFD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NCON</td>
</tr>
<tr>
<td>Pre-surgery</td>
<td>15.4 ± 2.7</td>
</tr>
<tr>
<td>48 weeks post-surgery</td>
<td>4.5 ± 0.8</td>
</tr>
<tr>
<td>(F(1.62) = 7.1; p&lt;0.005)</td>
<td></td>
</tr>
</tbody>
</table>

Group mean peak relative difference NCON versus CON at 48 weeks post-surgery 14.2%

| Table 7.8 | Summary of ATFD improvement following NCON versus CON ACL rehabilitation comparing pre-surgery to 48 weeks post-surgery. |
In general, the group mean peak relative difference in knee laxity associated with the injured limb, favouring NCON versus CON, was 14.2% of baseline.

As might be expected following ACL reconstruction surgery, both groups showed the ability to check excessive passive ATFD and both groups were within <5mm compared to the non-injured knee, which is considered normal or nearly normal (Woo et al. 2002). Furthermore, the amount of decreased ATFD found over the 48 week assessment period is similar to the levels of decreased anterior-posterior laxity reported by Angoules et al. (2013), and so probably representative of the type of gains that might be expected in a wider array of ACL-injured populations. The slight increase in ATFD seen at 12 weeks, compared to the 6 weeks test occasion, might be explained by the biological healing of the autologous graft (Fu et al. 1999, Oryan et al. 2013). Initial decreases in ATFD seen at the 6 weeks post-surgical test occasion, will be due to the pre-existing tension in the autologous graft tissue. However, this lessens as the graft is subjected to a period of necrosis and it is usual to see an increase in ATFD during this process before the onset of the revascularisation (Fu et al. 1999, Oryan et al. 2013). From approximately 6 weeks and up to 18 months following surgery, the graft increases its blood supply from its bony insertions as it undergoes a complete remodelling process (Fu et al. 1999, Oryan et al. 2013).

Both groups will have been subjected to the same healing process, yet the NCON group showed superior results in the reduction of joint laxity. This might be attributed to the knee experiencing a more robust system of rehabilitation conditioning, possibly derived from improvements in
neuromuscular control, which enabled a better healing environment for the graft.

In summary, this study provides evidence that NCON rehabilitation improves ATFD compared to the traditional CON rehabilitation. However, the results for joint laxity for both groups give a clinically successful outcome.

7.4.2 Is there evidence that NCON rehabilitation improves neuromuscular performance as measured by peak force (PF) in the knee extensors and flexors, following ACL reconstruction compared to traditional CON practice?

Reduction in muscle strength is commonly seen following injury and surgery. This can occur due to reduction in normal activity and function and/or due to arthrogenic inhibition (Hopkins and Ingersoll 2000, Rice and McNair 2010). In order to restore function and lessen the likelihood of further injury, it is imperative that adequate levels of strength are gained.

Peak force (PF) is the maximal voluntary muscle activation (MVMA) that an individual can muster and it is used as a measurement of muscle strength. The method of measuring peak force used in the study to identify differences between NCON and CON rehabilitation following ACL surgery, is described in Chapter 3 – Sections 3.8.2 and 3.8.3. Similar methods have previously been tested for reliability and reproducibility and have been reported in Chapter 2 – Section 2.6.3. The intra-session group mean coefficient of variation score for the knee flexors has been reported as $3.5 \pm 1.9\%$, suggesting that 2 trials using this method is sufficient in discriminating an individual’s performance change of $\pm 5\%$ (95% confidence level). The method used for the randomised control trial described in this thesis used the mean of 3 maximal volitional muscle
activations, ensuring a good level of discrimination of a patient’s performance within the same test session, and especially within the context of the experimental ‘power’ associated with the design of the thesis’ RCT. However, the inter-day group mean coefficient of variation score for knee extensors has been reported as 6.6 ± 3.0% and knee flexors 8.5 ± 3.3% (Gleeson et al. 2002, Minshull et al. 2009). The intra-class correlation coefficient and corresponding standard error of single measurement (95% confidence levels) for knee extensors 0.99 and 9.5%, respectively, and for knee flexors 0.93 and 7.8%, respectively (Gleeson et al. 2002, Minshull et al. 2009). The authors state that the reliability of this method of measuring PF exceeds the 0.80 threshold of clinical acceptability (Currier 1984). In the context of the assessment of the individual rather than the assessment of group mean responses, the authors suggest at least 5 - >25 replicates of PF measurement is required to identify between scores of different individuals with a ± 5% level of precision. Within the context of clinical populations, post-operative patients would not be able to tolerate numerous maximal efforts and the clinician would not be afforded such an extensive assessment time. It could be argued that the ± 5% level of precision is not necessary when assessing post-operative ACL patients as the changes in individual’s scores are likely to be high. Nevertheless, the consideration of clinimetric utility associated with the PF assessment of individual patients is somewhat moot, as it should be remembered that the focus of the RCT is that of differences between group mean responses.

The outcomes for extensor PF, measured by factorial ANOVA with repeated measures showed significant leg (injured/ non-injured), by test occasion (pre-, 6, 12, 24, and 48 weeks post-operative) (F(1.6, 99.6)GG = 89.8; p<0.005) interaction. In addition, this also showed significant group (NCON/
CON) by test occasion (pre-, 6, 12, 24, and 48 weeks post-operative) \((F_{(1.4, 84.8)} \text{GG} = 4.0; \ p < 0.05)\). Equivalent biostatistical testing for knee flexor PF showed similar patterns of interaction response, leg by test occasion \((F_{(2.4, 147.4)} \text{GG} = 58.4; \ p < 0.005)\) and group by test occasion \((F_{(2.5, 152.3)} \text{GG} = 5.8; \ p < 0.005)\). Though the patterns of improvement in strength over time were dependent on which leg was being assessed and whether the patient had undergone NCON or CON rehabilitation, the strength performance between the injured and non-injured legs were not influenced by NCON or CON training. As the rehabilitation was administered to the patient holistically, both legs were subject to the same amount of conditioning. Possibly the non-injured leg might have been subjected to slightly more conditioning initially due to the compensatory role it will have taken during the first few weeks following surgery. It might also be reasonable to assume that the non-injured leg would have been deconditioned prior to the surgery, due to limited function that ensued following the initial ACL injury. It is therefore not surprising that the non-injured leg has also shown beneficial gains in strength.

The most significant effect associated with the overall interaction, showing NCON to be the most beneficial form of rehabilitation in either maintaining or re-establishing strength for knee extensors, was seen at 6 weeks and 24 weeks post-surgery. In comparison, the NCON group knee flexors showed superior interaction at 6 weeks and 12 weeks post-surgery. Table 7.9 summarises the key findings.
<table>
<thead>
<tr>
<th>Test Occasion</th>
<th>Knee Extensors Peak Force (N)</th>
<th>Knee Flexors Peak Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NCON</td>
<td>CON</td>
</tr>
<tr>
<td>Pre-</td>
<td>372 ± 127</td>
<td>374 ± 68</td>
</tr>
<tr>
<td>6 weeks</td>
<td>325 ± 78</td>
<td>298 ± 64</td>
</tr>
<tr>
<td></td>
<td>$F_{(1, 62)} = 5.8; p&lt;0.05$</td>
<td>$F_{(1, 62)} = 6.1; p&lt;0.05$</td>
</tr>
<tr>
<td>12 weeks</td>
<td>224 ± 54</td>
<td>190 ± 48</td>
</tr>
<tr>
<td></td>
<td>$F_{(1, 62)} = 13.1; p&lt;0.001$</td>
<td></td>
</tr>
<tr>
<td>24 weeks</td>
<td>383 ± 93</td>
<td>350 ± 77</td>
</tr>
<tr>
<td></td>
<td>$F_{(1, 62)} = 9.3; p&lt;0.005$</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.9 Summary of PF (knee flexors and extensors) improvement associated with the assessment occasion demonstrating the most significant interaction following NCON versus CON ACL rehabilitation.

At 6 weeks post-surgery both the knee extensors and flexors are weaker than pre-operatively. The knee extensors associated with the NCON group show a 13% loss compared to a 20% loss for the CON group at 6 weeks post-surgery. The knee flexors associated with NCON group also show a strength loss of 15.0% at 6 weeks post-surgery, compared to a 24.1% loss associated with the CON group. Loss of PF can be expected at this stage in recovery, due to initial restrictions placed on function resulting from both the insult of the surgery and the post-operative rehabilitative restrictions introduced to protect the immature autologous graft. However, the amount of loss in PF is less for the patients who underwent NCON rehabilitation for both the knee extensors and flexors, compared to CON rehabilitation. It is plausible that the characteristics of NCON conditioning account for a reduction in the interference effect (discussed in Chapter 2 – Section 2.8.7), and that this contributes to the beneficial reduction in the extent of the post-surgery deconditioning.

Although, on completion of this thesis, no recommendations regarding minimal clinically important difference (MCID) could be identified, the amount
difference in PF measured at the 6 weeks test occasion might be sufficient to influence clinical practice, especially as the limitation of deconditioning of muscle strength following surgery might offer the graft better protection and a more conductive healing environment. Also, it could potentially lessen the risk of further injury and ensure a smoother transition into the next phase of rehabilitation.

At the 12 week post-surgery test occasion, the knee flexors in the NCON group had exceeded the pre-operative measure by 3.7%, whereas, the CON group was still suffering a 10.1% loss of pre-operative strength. The knee flexors are likely to have received more conditioning at this point in the rehabilitation as compared to the knee extensors. The ACL rehabilitation guideline that had been followed did not recommend open kinetic chain quadriceps exercises until approximately the 12 week stage [see Appendix A - RJAH anterior cruciate ligament rehabilitation guide]. This might be the reason why the flexors had showed a greater interaction at this point. Once again, although no MCID could be found, it is reasonable to assume that a 3.7% gain in strength is clinically relevant and desired compared to a 10.1% loss in peak force. As discussed in Chapter 2 - Section 2.2.2, the hamstring muscle group and the quadriceps: hamstring ratio is thought to be significant in ACL injury prevention, and is a focus in ACL rehabilitation programmes (Griffin et al. 2005, Blackburn et al. 2009, Alentorn-Geli 2009, van Grinsven et al. 2010, Lobb et al. 2012, Manske et al. 2012). Earlier restoration of hamstring strength is advantageous.

At 24 weeks following surgery, the NCON group showed a 4% improvement in knee extensor peak force compared to pre-operatively. In comparison, the CON group demonstrated a 6% loss in knee extensor peak
force from pre-surgery to 24 weeks post-surgery. From 12 weeks post ACL surgery, emphasis on quadriceps conditioning starts [Appendix A - RJAH anterior cruciate ligament rehabilitation guide]. Therefore, it is not surprising that a greater interaction in the knee extensors are seen at the 24 weeks test occasion compared to the 12 weeks test occasion for the knee flexors. Once again, NCON rehabilitation showed superior results, giving some credence to the possibility of that a detrimental interference effect is caused by training for both cardio-vascular endurance and strength within the same rehabilitation session, causing attenuation in strength gains. The interpretation is in agreement with the findings from the systematic literature review investigation the incompatibility of CON training (Chapter 2 – Section 2.8.6.1).

From pre-surgery to the 48 week post-surgery, the mean relative improvement in peak force for the knee extensors and flexors of the injured limb for both the NCON and CON groups, are shown in table 7.10.

<table>
<thead>
<tr>
<th>Injured limb</th>
<th>Peak Force (N) Pre-surgery</th>
<th>Peak Force (N) 48 weeks post-surgery</th>
<th>Improvement in Peak Force (N)</th>
<th>Percentage Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NCON</td>
<td>CON</td>
<td>NCON</td>
<td>CON</td>
</tr>
<tr>
<td>Extensors</td>
<td>360±40</td>
<td>360±35</td>
<td>420±35</td>
<td>390±50</td>
</tr>
<tr>
<td>Flexors</td>
<td>210±10</td>
<td>210±10</td>
<td>260±5</td>
<td>240±30</td>
</tr>
</tbody>
</table>

Table 7.10 Mean relative improvement in PF (knee extensors and flexors) from pre-surgery to 48 post-ACL surgery associated with the injured limb.

The percentage improvement in the knee extensors and flexors for the NCON group are similar to the improvements found by authors who report an interference effect, such as Dudley et al. (1985), Hunter et al. (1987), Hennessy
et al. (1994), Sale et al. (1990), Nelson et al. (1990) and Häkkinen et al. (2003). The increases in the strength groups (NCON) found by these authors ranged from 14 – 26%. However, direct comparisons cannot be truly relied upon, as the populations assessed in these previous studies were healthy individuals and the duration of the assessment period ranged from 8 weeks to 21 weeks. In addition, other authors reporting an interference effect also found larger improvements in strength [29 – 68%: Hickson (1980), Kraemer et al. (1995), Bell et al. (2000), Cadore et al. (2010)]. Furthermore, the studies that provide no evidence following CON training to support the hypothesis of an interference effect, reported percentage strength gains ranging from 8% - 40% for the strength only groups (NCON) (Bell et al. 1991, Volpe et al. 1993, McCarthy et al. 1995, Gravelle and Blessing 2000, McCarthy et al. 2002, Balabinis et al. 2003, Leveritt et al. 2003, Kraemer et al. 2004, Glowacki et al. 2004, Karavirta et al. 2011). However, once again, no direct comparisons can be made with the RCT presented in this thesis, due to the differences in methodology, populations, duration of the studies and the volume and intensity of the training performed (refer to Chapter – 2 – Section 2.8.5 - Tables 2.6 and 2.7).

In general, over the 48 weeks assessment of PF, the group mean relative difference in improvement of patients’ injured knee strength, was 9% for the knee extensors and 6% for the knee flexors. The advantage of NCON rehabilitation adhered to in the first 24 weeks post-operatively is less by the 48 week test occasion. As previously discussed in this chapter, this might be due to the patients resuming normal functional activities which don’t include the segregation of strength- and cardio-vascular-focused exercise.

The relative effect sizes associated with NCON versus CON rehabilitation over the study duration of 48 weeks, ranged from -0.5 loss to 0.1
gain in the injured leg's performance for the NCON group. This was favourable in comparison to the overall loss in performance associated with the traditional CON practice, where the peak effects ranged from -0.8 to -0.3. This shows NCON training is the most efficacious, and preferable to CON for improving in peak force. These effect sizes compare favourably with the peak effect sizes for strength improvements calculated from the results documented in previous literature and reviewed in Chapter 2 – Section 2.8.5 – Tables 2.8 and 2.9. Tables 7.12 and 7.13 are copied from Chapter 2 for convenience of comparison.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Effect Size</strong></td>
<td><strong>range</strong></td>
<td><strong>d</strong></td>
<td><strong>SE</strong></td>
<td><strong>d</strong></td>
<td><strong>SE</strong></td>
<td><strong>d</strong></td>
<td><strong>SE</strong></td>
<td><strong>d</strong></td>
<td><strong>SE</strong></td>
<td><strong>d</strong></td>
<td><strong>SE</strong></td>
</tr>
<tr>
<td><strong>S</strong></td>
<td>3.35 – 0.65</td>
<td>-</td>
<td>0.28 – 0.84</td>
<td>S: 0.07 – 1.17</td>
<td>E: 0.02 – 0.2</td>
<td>SE: 0.13 – 1.03</td>
<td>SE: 0.06 – 1.03</td>
<td>E: 0.01 – 0.99</td>
<td>SE: 0.06 – 1.03</td>
<td>U: 0.02 – 0.84</td>
<td>SE: 2.12 – 2.39</td>
</tr>
<tr>
<td><strong>E</strong></td>
<td>2.39 – 0.62</td>
<td>-</td>
<td>0.23 – 0.45</td>
<td>SE: 0.14 – 1.19</td>
<td>SE: 0.13 – 1.03</td>
<td>E: 0.04 – 1.72</td>
<td>SE: 0.04 – 1.22</td>
<td>SE: 0.01 – 0.13</td>
<td>SE: 0.02 – 1.46</td>
<td>SE: 0.14 – 0.27</td>
<td></td>
</tr>
<tr>
<td><strong>SE</strong></td>
<td>2.12 – 2.39</td>
<td>-</td>
<td>0.23 – 0.45</td>
<td>SE: 0.14 – 1.19</td>
<td>SE: 0.13 – 1.03</td>
<td>E: 0.04 – 1.72</td>
<td>SE: 0.04 – 1.22</td>
<td>SE: 0.01 – 0.13</td>
<td>SE: 0.02 – 1.46</td>
<td>SE: 0.14 – 0.27</td>
<td></td>
</tr>
</tbody>
</table>

S: Strength group.
E: Cardio-vascular endurance group.
SE: Combined strength and cardio-vascular endurance group.

**Table 7.12** Effect sizes associated with concurrent (SE) versus non-concurrent (S and E) conditioning and attenuation of strength gains [Information as shown in Table 2.8 for ease of reference].
Table 7.12  Effect sizes associated with concurrent (SE) versus non-concurrent (S and E) conditioning and no attenuation of strength gains [Information as shown in Table 2.9 for ease of reference].

In summary, from the findings presented in this thesis, there is evidence NCON rehabilitation does show greater improvements in peak force associated with both the extensors and flexors compared to traditional CON rehabilitation.

7.4.3 Is there evidence that NCON rehabilitation improves neuromuscular performance as measured by rate of force development (RFD) in the knee extensors and flexors, following ACL reconstruction compared to traditional CON practice?

Rate of force development (RFD) is associated with the dynamic stability of the knee (Zebis et al. 2011). It is described as the rapidity with which physiological meaningful levels of force can be generated (Minshull et al. 2009, Hannah et al. 2012). Furthermore, both sexes have similar capacity to develop RFD (Hannah et al. 2012). The RFD is an important factor in the dynamic
stability of the knee as higher rates of force development are thought to stiffen
the joint complexes quickly and lessen the likelihood of injury (Gruber et al.
2004). In addition, as it is suggested that sufficient muscle activity must occur
within a 30 – 70 millisecond window from the onset of joint loading to protect the
ACL, RFD is an advisable adjunct measure following ACL injury and

The method used to assess RFD is outlined in Chapter 3 – Section 3.8.3,
and is similar to the method used by Gleeson et al. (2002) and Minshull et al.
(2009). These authors have addressed the inter-day reproducibility and
reliability of this measurement method and the group mean coefficient of
variation for the knee extensors has been reported to be 20.3 ± 12.1% and for
the knee flexors 20.7 ± 9.2%. The intra-class correlation coefficient and the
associated standard error of measurement (95% confidence levels) for the knee
extensors was 0.91 and 42.2% respectively and the knee flexors was 0.81 and
24.5%. Both studies demonstrated RFD has a limited capability of
discriminating subtle changes in performance, especially so in the knee flexors
during intra-individual comparisons. In the context of the assessment of intra-
individual differences, only RFD associated with knee extensors exceeded the
clinically acceptable reliability coefficient threshold of >0.8 (Currier 1984). Due
to the limited capacity to discriminate any physiological change based on a
single trial assessment with intra-group comparisons, the authors suggest
calculating the mean of multiple trials. In order to achieve an arbitrary level of
±5% (95% confidence levels) a mean score of >25 trials would be required. As
with assessing peak force, this number of trials would not be clinically or
practically acceptable for the post-operative ACL population investigated in this
thesis. The consideration of clinimetric utility associated with the RFD
assessments of individual patients is important but should be evaluated within the focus of the RCT, which is differences between group mean responses. In this respect, the experimental ‘power’ associated with RFD within the design of the thesis’ RCT had been established effectively. The mean of 3 trials were used in this thesis’s investigation.

Within this thesis, the results comparing the effects of NCON versus CON rehabilitation on RFD were generated by factorial ANOVA with repeated measures. The knee extensors showed significant leg (injured/ non-injured) by test occasion (pre-, 6, 12, 24, and 48 weeks post-surgery) ($F_{(1.6, 96.9)} = 48.9; p<0.005$), and also by group (CON/ NCON) by test occasion (pre-, 6, 12, 24, and 48 weeks post-surgery) ($F_{(1.6, 97.5)} = 3.5; p<0.05$). The equivalent biostatistical testing of the hypothesis for the knee flexors showed significant leg (injured/ non-injured) by test occasion (pre-, 6, 12, 24, and 48 weeks post-surgery) ($F_{(1.8, 110.1)} = 34.4; p<0.005$) and also by group (CON/ NCON) by test occasion (pre-, 6, 12, 24, and 48 weeks post-surgery) ($F_{(1.7, 106.5)} = 5.7; p<0.005$). These findings suggest that the patterns of improvement in RFD were different for the injured and non-injured legs and that NCON conditioning offered enhanced patterns of recovery for both the knee extensors and flexors. Table 7.13 highlights the results found at the 12 weeks assessment occasion where the greatest effects of interaction occurred associated with RFD increases during the 48 week test period.
Table 7.13  Summary of RFD (knee flexors and extensors) improvement following NCON versus CON ACL rehabilitation for both the injured and non-injured limbs at pre-surgery and 12 weeks post-surgery.

The results show that NCON and CON rehabilitation improved RFD with the greatest interaction occurring at the 12 week post-surgery test occasion. However, NCON rehabilitation showed greater gains in RFD in both legs and for both the knee extensors and flexors between pre-surgery and 12 weeks post-surgery. The effect sizes associated with the pre- to 12 weeks post-operative phase for the NCON group injured knee extensors and flexors were 0.71 and 0.54 respectively. The effect sizes associated with the pre- to 12 weeks post-operative phase for the CON group injured knee extensors and flexors were 0.56 and 0.04 respectively.

Once again improvements were seen in both legs and this is likely to be attributed to the holistic nature of the rehabilitative exercises. Greater improvements are seen at the 12 week post-surgical test period and this might be related to the type of exercises and the reduction in post-operative arthrogenic inhibition at this stage. Greater improvements occurred in the NCON group compared to the CON group.
In relation to previous literature, Häkkinen et al. (2003) studied 32 previously untrained male subjects, comparing a pure strength training group with a combined strength and cardio-vascular training group, and while no significant differences were found in peak force at the 5 test occasions during the 21 week assessment period, a greater improvement of approximately 85% in RFD was identified in the isolated strength group compared to the concurrent group. The differences between this study (Häkkinen et al. 2003) and the RCT described in this thesis, relate to the definition of concurrent training. The concurrent group in Häkkinen et al.’s (2003) study trained for both strength and cardio-vascular endurance, but on separate days, and the non-concurrent group comprised solely of strength training. The concurrent group in this thesis trained for both strength and cardio-vascular endurance on the same day, in the same rehabilitation session, and the non-concurrent group performed the same volume of exercises, but on separate days. In addition, the conditioning of the concurrent group in the study by Häkkinen et al. (2003) was not iso-volumetric by comparison to the non-concurrent group, nor was it addressing a post-operative population. Nevertheless, a precedence of the possibility of attenuation of RFD has been previously identified. Häkkinen et al. (2003) reasoned that the improvement in RFD was due to the possibility that rapid voluntary neural activation might be inhibited by cardio-vascular endurance training, and suggesting the possibility of an interference effect affecting explosive strength development. However, as discussed previously in Chapter 2 – Section 2.8.7, there is no consensus on what might drive the interference effect. Suggested possibilities are fatigue, overtraining, increases in catabolic state, changes in muscle fibre type, but perhaps the suggestion most closely related to RFD might be potential changes in motor unit recruitment patterns.
Interestingly, the most significant effect contributing to the group by time interaction in PF associated with the knee extensors, was seen at 24 weeks post-surgery, while the most significant interaction for the knee extensors RFD was seen at 12 weeks post-surgery. Perhaps RFD is more responsive to NCON training in the acute phases and/or RFD might be sufficiently initiated with different types of rehabilitative exercises compared to PF. As previously mentioned, open kinetic chain quadriceps exercises are not introduced until approximately 12 weeks post ACL reconstructive surgery. However, closed kinetic chain exercises are commenced as soon as the patients symptoms allow. Thus, RFD might respond more to the speed, co-ordination and pattern of movement rather than to an isolated muscular effort (ACSM 2002, Häkkinen et al. 2003).

In general, the group mean peak relative difference in the improvement of RFD in the injured leg associated with NCON versus CON at 48 weeks post ACL reconstruction surgery was 7.9% for the knee extensors and 15.3% for the knee flexors, using the non-injured leg’s RFD as the baseline. While the interaction wasn’t as large at 48 weeks compared to 12 weeks post-operatively, the NCON group maintained the superior RFD compared to the CON group. This occurred despite the likelihood of patients returning to normal activities of daily living and recreation from 24 weeks post-surgery. Possibly the maintenance of improvement, particularly in the knee flexors at the 48 weeks assessment occasion, might be due to the hamstring rehabilitative bias.

While an improvement of RFD in both the NCON and CON groups were identified, a deficit in the knee extensors compared to the non-injured limb (pre-
surgery) is still present at 48 weeks post-surgery. The extent of the deficit was by approximately 16% for the knee extensors in the CON group and 9% for the NCON group. By contrast, the knee flexors at 48 weeks post-surgery of the injured limb reached parity to the non-injured limb pre-operatively in the CON group and exceeded baseline performance by 22% in the NCON group. Previous literature has also reported reduction in RFD following ACL reconstruction surgery (at the 24 week stage) by an investigation into whether RFD could be used as an adjunctive outcome measure in a return to sport decision following ACL reconstruction by Angelozzi et al. (2012). However, this study didn’t assess the knee extensors or flexors in isolation. In order to measure RFD associated with the knee flexors and extensors, a leg press machine had been used. Furthermore, the study by Angelozzi et al (2012) reported similar findings to the random control trial presented in this thesis, showing the RFD deficits were present despite a nearly full recovery as measured by IKDC. However, in contrast, Angelozzi et al. (2012) found RFD did reach similar levels to baseline by 48 weeks. In addition to the assessment methodology, there are differences in the populations tested. The study by Angelozzi et al (2012) examined male soccer players exclusively compared to mixed sex and varied levels of sporting prowess of the population addressed in this thesis.

In summary, there is evidence that NCON rehabilitation improves RFD compared to the traditional CON rehabilitation following ACL reconstructive surgery, suggesting the possibility RFD is attenuated when strength and cardio-vascular endurance exercises are administered in a CON format.
7.4.4 Is there evidence that NCON rehabilitation improves neuromuscular performance as measured by electromechanical delay (EMD) in the knee extensors and flexors, following ACL reconstruction compared to traditional CON practice?

Electromechanical delay (EMD) is the time lag between the onset of electrical activity and the onset of tension being developed in muscle and is attributed as one aspect of overall neuromuscular reaction time (Vos et al. 1990, Winter and Brooks 1991, Zhou et al. 1995, 1996, Minshull et al. 2007, 2009, Hannah et al. 2012). In addition, EMD like RFD, has a similar capacity across both sexes (Winter and Brooks 1991, Hannah et al. 2012). It has been identified in decreasing the risk of injury (Ristanis et al. 2009), and plays a role alongside other neuromuscular factors in the dynamic stability of the knee, as discussed in Chapter 2 – Section 2.3. Therefore, it was deemed insightful to measure EMD following ACL reconstruction and the new sequencing of rehabilitation used in the main study within this thesis (Chapter 5).

The methodology is fully outlined in Chapter 3 – Section 3.8.3. This method is similar to those used in previous studies which have addressed the reproducibility and reliability of this type of testing (Viitasalo et al. 1980, Minshull et al. 2009). Table 7.14 summaries the results from Minshull et al. (2009).

<table>
<thead>
<tr>
<th></th>
<th>V%</th>
<th>R_i</th>
<th>SEM% (95% confidence levels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intra-session</td>
<td>10.1 ±3.4</td>
<td>0.80 ±0.06</td>
<td>10.8 ±1.8</td>
</tr>
<tr>
<td>Inter-day</td>
<td>14.5 ±5.5</td>
<td>0.64 ±0.09</td>
<td>15.9 ±3.1</td>
</tr>
</tbody>
</table>

Table 7.14Summary of reproducibility and reliability in measurement of EMD demonstrated by Minshull et al. (2009).
These results suggested that the context of the assessment of an individual patient, EMD has a limited capability to detect any physiological change based on a single trial assessment, similar to RFD discussed in Chapter 2 – Section 2.6.5. Using the central limit theorem, more than 15 trials would be required to achieve a discretionary acceptable level of error ±5% (95% confidence level) (Minshull et al.2009). This number of trials would not be feasible in a post-operative clinical population. Therefore, the same discretionary caution should be applied when evaluating the intra-individual results of EMD as for RFD. The consideration of clinimetric utility associated with EMD assessment of individual patients is an important consideration for clinical efficacy. However, the outcome of EMD within the focus of the thesis’ RCT, which is the differences between group mean responses, offers sufficient experimental ‘power’ within the design of the RCT. The mean of 3 trials were used in this thesis’s investigation.

As part of the RCT performed as the basis of this thesis (Chapter 5), the effect of NCON versus CON ACL rehabilitation on EMD was assessed using factorial ANOVA with repeated measures. The EMD results showed significant interactions for the knee extensors for leg (injured/ non-injured) by test occasion (pre-, 6, 12, 24, 28 weeks post-surgery) \( (F_{(1.5, 93.2)GG} = 155.9; p<0.005) \) and group (NCON/ CON) by leg (injured/ non-injured) \( (F_{(1.6, 97.5)GG} = 11.0; p<0.005) \). A similar interaction was found in the knee flexors for leg (injured/ non-injured) by test occasion (pre-, 6, 12, 24, 28 weeks post-surgery) \( (F_{(1.6, 100.4)GG} = 78.2; p<0.005) \) and group (NCON/ CON) by leg (injured/ non-injured) \( (F_{(1.0, 62.0)GG} = 8.4; p<0.005) \). These results suggest patterns of improvement in EMD over time were different for the injured and non-injured legs and that NCON rehabilitation offered enhanced patterns of recovery over time compared to the
CON group. The greatest improvements in EMD were found at 48 weeks post ACL reconstruction surgery. Table 7.15 shows the group mean scores following a priori testing of the hypothesis for relatively greater improvements in EMD over the assessment period.

<table>
<thead>
<tr>
<th>Test Occasion</th>
<th>Knee Extensors Electromechanical Delay (ms)</th>
<th>Knee Flexors Electromechanical Delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NCON Injured</td>
<td>NCON Non-injured</td>
</tr>
<tr>
<td>Pre-</td>
<td>59.5 ±18.4</td>
<td>29.6 ±12.9</td>
</tr>
<tr>
<td>48 weeks</td>
<td>29.0 ±11.7</td>
<td>37.4 ±13.2</td>
</tr>
</tbody>
</table>

Table 7.15 Summary of EMD improvements following NCON versus CON ACL rehabilitation at the pre-surgery and 48 weeks post-surgery assessment occasions.

The EMD values for m. vastus lateralis in the non-injured limb and the injured limb in both the CON and NCON groups at 48 weeks post-surgery ranged from ≈27 – 33 ms. Interestingly, Vos et al. (1990) measured EMD (m. vastus lateralis) of 5 healthy participants (2 female, 3 male) during an isometric knee extension contraction at 90º knee joint flexion and found slightly higher EMD values, ≈35 – 45 ms. The discrepancy in EMD times between this study (Vos et al. 1990) and the study presented in this thesis might be due the different testing methods and participants examined. However, one might expect the increased joint flexion angle (90º) and positioning of the subjected described by Vos et al. (1990) to have improved EMD times (compared to the study presented in this thesis), due to the increased stretch of m. vastus lateralis, providing a stiffer system. Indeed, improvements EMD (m. vastus
lateralis) times were demonstrated by Minshull et al. (2011), where increased knee flexion was shown to reduce EMD (m. vastus lateralis) in 12 healthy male participants, ≈25ms at 25º, ≈24ms at 35º and ≈19ms at 45º. Perhaps the variability of conditioning to which the participants had been subjected to might also have accounted for the slight differences in EMD times.

The group mean scores show lack of group by time and group by time by leg interactions for both the knee extensors and flexors. Nevertheless, a significant interaction of leg by group implies that NCON rehabilitation resulted in improved knee extensor and flexor EMD outcomes compared to the traditional CON rehabilitation. Furthermore, this was irrespective of the time point of which it was measured.

It is interesting that unlike PF and RFD, the improvement in EMD did not occur at a particular phase during the assessment period. Perhaps this alludes to EMD improving over time with increases in knee joint stability. For example, blood vessels and nerves will infiltrate the autologous graft tissue as it remodels and this will lead to reduced pathological laxity and possibly improved neural control of the joint. This in turn could provide a more efficient platform for the musculoskeletal and neuromuscular system. Therefore, in order to enable improvements in EMD, these elements might need to have been established previously. So alternatively, the EMD recovery might not have occurred at one particular assessment period due to the inability of this measure to detect smaller changes in outcome.

In general, the group mean peak relative difference in the improvement of EMD in the injured leg associated with NCON versus CON at 48 weeks post ACL reconstruction surgery was 10.1% for the knee extensors and 11.9% for the knee flexors. And the improvement of EMD in the non-injured leg associated
with NCON versus CON at 48 weeks post ACL reconstruction surgery was 3.2% for the knee extensors and 9.2% for the knee flexors. Greater improvement in the knee flexors is implied (but not assessed statistically) and this might be due to the bias in the rehabilitative exercises, or it might suggest that the knee flexors were more deconditioned or inhibited prior to surgery. However, this is at odds with a previous investigation, assessing EMD following hamstring ACL reconstruction surgery, where there was a significant increase in EMD at two years post-surgery (Ristanis et al. 2009). The authors go on to speculate that this might impair performance and lead to further injury (Ristanis et al. 2009). The difference in results might be due to the mixed graft choices used in the population presented in this thesis (approximately 70% were hamstring graft and 30% were patella tendon graft reconstructions).

In summary, NCON rehabilitation does show greater bilateral improvements in EMD for both knee flexors and extensors over the 48 weeks assessment period. Although no previous study has identified a minimal clinically important difference for EMD following ACL reconstruction, improvements of 10.1% and 11.9% could be reasonably accepted as clinically significant. A change in rehabilitative practice at no extra cost to gain an approximate ≥10% improvement in EMD and the associated benefits, might not be an unreasonable recommendation.
7.4.5 Is there evidence that NCON rehabilitation improves neuromuscular performance as measured by sensorimotor performance (SMP) in the knee extensors and flexors, following ACL reconstruction compared to traditional CON practice?

Sensorimotor performance is often termed proprioception and it comprises a complex interplay of neuromuscular factors, relying on both spinal and cortical projections and reflective pathways, thus it is very difficult to assess. Therefore, it should be of no surprise that a lack of measurement consensus exists (Saxton et al. 1995, Roberts et al. 2000, 2007, Beynnon et al. 2002, Ageberg et al. 2007, Angoules et al. 2011). Nevertheless, it plays an important role in ACL rehabilitation (Caraffa et al. 1996). Various studies addressed in Chapter 2 – Section – 2.6.6, have identified low to moderate measurement reliability across a variety of commonly-used indices, with intra-class correlation coefficients and standard error of measurement ranging from 0.16 – 0.99 and ≈8.6% – 14.7%, respectively (Kramer et al. 1997, Ageberg et al. 2007, Angoules et al. 2011). Therefore, as with RFD and EMD intra-individual results solely based on SMP should be viewed with some degree of caution from the perspective of measurement clinimetrics. In addition, the use of passive tests to measure SMP has been challenged by some authors (Kramer et al. 1997, Gokeler et al. 2012). Recently, it has been suggested that measurements involving an active neuromuscular system when assessing SMP is more closely associated with normal function (Gokeler et al. 2012).

The method of testing SMP as part of this thesis had to be practical for acceptable use in a NHS setting and to match limited financial resources to support the assessment protocols. Testing for force error (FE) initiates an
active neuromuscular system as the patient either extends or flexes the knee on an instructor's command, in order to match a blind target force (50% of his/her pre-operative PF). This assessment could be performed in a room with limited space, utilising the same assessment equipment used to measure PF. The complete methodology for assessing force error is described in Chapter 3 – Section 3.8.4.

The results for SMP using factorial ANOVA with repeated measures identified significant interactions in the knee extensors for leg (injured/ non-injured) by test occasion (pre-, 6, 12, 24 and 48 weeks post-surgery) \( (F_{(1.1, 69.9)}^G = 78.6; p<0.005) \). In addition, there was a significant group (NCON/CON) by leg (injured/ non-injured) interaction for SMP \( (F_{(1.0, 62.0)}^G = 7.3; p<0.01) \). The same interaction performance responses were identified for the knee flexors, leg by test occasion \( (F_{(1.1, 69.9)}^G = 78.6; p<0.005) \) and group by leg \( (F_{(1.0, 62.0)}^G = 7.3; p<0.01) \). This is a similar response to EMD, whereby an absence of interaction between all three factors (leg x group x time) exists. So while the patterns of SMP improvement over time were separately dependent on which leg was being assessed and under which rehabilitation regime had been adhered to (NCON had elicited better recovery), the difference in SMP responses between the injured and non-injured leg was similar throughout the 48 week trial. Progressive improvements in SMP were seen, but these were not particularly influenced at any time-phase in the rehabilitation.

The overall group mean force error (FE) scores associated with NCON versus CON rehabilitation identified from this study are represented in Table 7.16.
Table 7.16 Summary SMP improvement following NCON versus CON ACL-rehabilitation at the pre-surgery and 48 weeks post-surgery assessment occasions.

<table>
<thead>
<tr>
<th>Test Occasion</th>
<th>Knee Extensors SMP - Force Error (%)</th>
<th>Knee Flexors SMP - Force Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NCON</td>
<td>CON</td>
</tr>
<tr>
<td>Pre-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injured</td>
<td>18.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Non-injured</td>
<td>±7.3</td>
<td>±2.1</td>
</tr>
<tr>
<td>48 weeks</td>
<td>4.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Non-injured</td>
<td>±2.5</td>
<td>±2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( F_{1.0,62.0} GG = 7.3; p<0.01 \)

\( F_{1.0,62.0} GG = 7.1; p<0.01 \)

The effect sizes associated with this comparison (NCON versus CON) for the knee extensors of injured leg were 2.9 and 1.9, respectively; and for the knee flexors, 1.8 and 2.5, respectively. The significant interaction of group mean scores suggested that in contrast to all the other results produced from this study, CON rehabilitation might show greater improvement in SMP for the knee flexors compared to the NCON rehabilitation. However, due to the low to moderate reliability associated with SMP testing, some degree of caution should be applied as with RFD and EMD outcome scores.

In general, the group mean relative difference in SMP improvements in the patients undertaking NCON rehabilitation (compared to CON) at 48 weeks post-surgery for the knee extensors and flexors were 5.6% and 4.7% respectively, using the non-injured leg as the baseline.

The SMP results presented in this thesis vary from those of a previous study investigating differences between ACL graft types (Angoules et al. 2011). Although both studies show the regeneration of near normal proprioception, the study by Angoules et al. (2011) finds this occurs at an earlier time point of 24 weeks following surgery. However, there were differences in methodology...
between the study presented in this thesis and the study reported Angoules et al. (2011). Joint position sense and threshold to detect passive movement was assessed by Angoules et al. (2011) compared to the active generation of matching a force used in this thesis, and this might account for the disparity. The passive methods of assessing SMP have been criticised recently, suggesting that they provide limited evidence in assessing function following ACL surgery and that active assessments are more relevant (Gokeler et al. 2012). The study presented in this thesis assessed SMP by measuring force error (FE) thus activating the musculoskeletal and neuromuscular system. As Gokeler et al. (2012) suggests an active assessment is more relevant in assessing SMP; the results from this thesis might therefore be more pertinent than those passively-measured SMP results reported by Angoules et al. (2011).

Interestingly, bilateral deficits have been found at 2 years following surgery in ACL populations compared with healthy non-injured individuals (Roberts at al. 2000). Unfortunately, this study cannot answer whether this SMP discrepancy was present prior to, or how the pattern of improvement or deterioration occurred during the time of assessment. The results from the study, presented in Chapter 5 – Section 5.4.2.5, does not show this to be the case at the 48 week assessment point; however, it is plausible SMP might decline with time.

Speculatively, it might be that the improvement in SMP at 48 weeks found in this study, is associated with improvement in joint laxity (ATFD) as the latter will provide a passively stable joint and making it easier to control by neuromuscular system.

In summary, both NCON and CON rehabilitation improved SMP following ACL reconstructive surgery. There was no set time point where the greatest
interaction effects had occurred and this was similar to the improvement patterns seen in EMD. This observation might be associated with a limited ability to identify small changes in improvement or this steady improvement progression could be related to the developing stability of the knee. There is evidence that NCON rehabilitation provides greater SMP improvement in the knee extensors, but not in the knee flexors, compared to the traditional method of CON rehabilitation.

**Thesis Question**

ii) Is there evidence that NCON rehabilitation improves objectively-measured outcomes of functional, musculoskeletal and neuromuscular performance following ACL rehabilitation compared to traditional CON practice?

**Key Findings**

[Chapter 5]

- Beneficial gains were seen in all the objective measures in both groups for both limbs over the rehabilitation period.
- The NCON group out-performed the CON group in every outcome (with the exception of SMP for knee flexors).
- The percentage advantage of NCON rehabilitation versus CON at the 48 weeks assessment stage is outline in below:

<table>
<thead>
<tr>
<th>48 weeks assessment</th>
<th>NCON % advantage (injured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOP</td>
<td>6.3***</td>
</tr>
<tr>
<td>ATFD</td>
<td>14.2***</td>
</tr>
<tr>
<td>PF</td>
<td>Ext 5.4*, Flex 5.9*</td>
</tr>
<tr>
<td>RFD</td>
<td>7.9*, 15.3*</td>
</tr>
<tr>
<td>EMD</td>
<td>9.3*, 11.9***</td>
</tr>
<tr>
<td>SMP</td>
<td>5.6*, 4.7**</td>
</tr>
</tbody>
</table>

* = (p<0.05) ** = (p<0.01) *** = (p<0.005)

- The most significant interactions were found to occur at 12 and 48 weeks post-operatively.

**Table 7.17** Summary of the key findings associated with the thesis aim, to assess the effects of reconstruction surgery and 24 weeks of NCON rehabilitation (with 48 week post-operative follow-up) on objectively-measured function (HOP), musculoskeletal (ATFD) and neuromuscular performance (PF, RFD, EMD and SMP) compared to traditional CON rehabilitation, in patients with ACL deficiency.
7.4.6 Does clinical and/or social approbation associated with increased assessor-patient interactions influence objective function (HOP), musculoskeletal (ATFD) and neuromuscular performance (PF, RFD, EMD, SMP)?

As previously mentioned in this chapter (Section 7.2.4) a third group rehabilitated using the traditional CON method, was assessed on two occasions only, pre-operatively and at 48 weeks post-operatively. This enabled an investigation of potential bias brought about by assessor-patient interaction during the testing occasions.

The outcome was similar to that of assessor-patient interaction associated with the subjective measures, IKDC, KOOS and PP. No evidence of clinical approbation was found relating to HOP or to the musculoskeletal and neuromuscular outcomes. Therefore, the improvements in both the CON and NCON groups were likely to be properly attributed to healing and the rehabilitation, and where indicated statistically, to advantages associated with NCON conditioning.

In summary, this quality-control measure identified that the results from this study were not influenced by the interaction of the patient with the administrator during the assessment occasions.
7.5 Conclusion: Is there evidence that NCON rehabilitation improves self-perceived (subjective) outcomes of function and objectively-measured outcomes of functional, musculoskeletal and neuromuscular performance following ACL reconstruction compared to traditional CON practice?

The previous sections in this chapter have discussed and contextualised the results generated from the RCT described in Chapters 4 and 5. For the primary outcomes of function [(subjective) IKDC, KOOS, PP and (objective) HOP] and the secondary objective outcome measures of ATFD, PF, RFD, EMD and SMP, greater statistically significant improvements were demonstrated when NCON rehabilitation had been used compared to CON. Although it is difficult to establish from previous research an agreed MCID for all of these specific measures, it could be argued that up to a 15% improvement in outcomes following ACL surgery might represent sufficient clinical efficacy. This in turn might warrant a change in the way rehabilitative exercises are prescribed (Clark 2001, Collins et al. 2011, Irrgang et al. 2012, Di Stasi et al. 2012), especially as this type of rehabilitation requires no extra cost to the patient or the NHS. This is of course, with the one exception of SMP associated with the knee flexors of the injured limb, which showed greater improvements when CON rehabilitation is adhered to. However, given the caution which should be applied when measuring SMP based on previous reliability measurements (Kramer at al. 1997, Ageberg et al. 2007, Angoules et al. 2011) then this might be an anomaly. Whether this is the case or not, the weight of the findings from this RCT and previous literature would suggest NCON rehabilitation provides superior functional, musculoskeletal and neuromuscular outcomes (Hickson 1980, Dudley et al. 1985, Hunter et al. 1987,
Sale et al. 1990, Nelson et al. 1990, Bell et al. 1991, Hennessy and Watson 1994, Kraemer et al. 1995, Bell et al. 2000, Häkkinen et al. 2003, Santtila et al. 2009, Cadore et al. 2010, Karavirta et al. 2011). This supports the opinion that NCON training is better than CON rehabilitation training as it reduces the potential for an ‘interference effect’. However, as previously discussed, no consensus regarding the exact cause of this effect exists and the cause can only be surmised (Chromiak et al. 1990, Kraemer et al. 1995, Bell et al. 1997, Docherty and Sporer 2000, Wilson et al. 2012).

The suggested mechanisms for the ‘interference effect’ have included overtraining or overreaching due to the increased volume used in most of the studies assessing CON versus NCON training (Chromiak et al. 1990, Kraemer et al. 1995, Bell et al. 1997, Docherty and Sporer 2000, Wilson et al. 2012). The RCT presented in this thesis went to great lengths to ensure that both the volume and the intensity of rehabilitation were matched across the experimental groups being compared. Nevertheless, the findings in this thesis infer the existence of an interference effect whose mechanism of effect was therefore independent of exercise volume and intensity. In addition, when the literature was scrutinised (Chapter 2 - Tables 2.6 and 2.7), similar levels of exercise volume and intensity variability were present in both the literature supporting and opposing an interference effect (Hickson 1980, Dudley et al. 1985, Hunter et al. 1987, Nelson et al. 1990, Bell et al. 1991, Volpe et al. 1993, Hennessy et al. 1994, McCarthy et al. 1995, Kraemer et al. 1995, Bell et al. 2000, Gravelle et al. 2000, McCarthy et al. 2002, Leveritt et al. 2003, Balabinis et al. 2003, Häkkinen et al. 2003, Glowacki et al. 2004, Kraemer et al. 2004, Santtila et al. 2009, Cadore et al. 2010, Karavirta et al. 2011). Therefore, it might be reasonable to assume that overtraining and overreaching cannot be solely
responsible for strength attenuation when training in a CON format. No previous studies have assessed the comparable effect of NCON versus CON rehabilitation on injured or post-surgical populations, nor have any studies reported the effect on IKDC, KOOS, PP, HOP, ATFD, EMD or SMP outcomes.

The extent of the formal NCON versus CON rehabilitation was 24 weeks in duration and it is in accordance to the recommended routine ACL rehabilitation time-frame [see Appendix A - RJAH anterior cruciate ligament rehabilitation guide]. This time span is in excess of any of the studies examined in the literature review. The duration of the previous studies and separation of training ranged from 6 to 21 weeks (Hickson 1980, Dudley et al. 1985, Hunter et al. 1987, Sale et al. 1990, Nelson et al. 1990, Bell et al. 1991, Volpe et al. 1993, Hennessy and Watson 1994, Kraemer et al. 1995, McCarthy et al. 1995, Gravelle and Blessing 2000, Bell et al. 2000, McCarthy’s 2002, Häkkinen et al. 2003, Balabinis et al. 2003, Leveritt et al. 2003, Kraemer 2004 Glowacki et al. 2004, Santtila et al. 2009, Cadore et al. 2010, Karavirta et al. 2011). Therefore, the assessment period of the study presented in this thesis has examined the effects of increased longevity of such exercise sequencing, over 24 weeks. In addition, the follow-up assessment of 48 weeks post-surgery suggests the preservation of the superior benefits gained from the 24 weeks of supervised NCON rehabilitation.

The main aim of this thesis was “to assess the effects of reconstruction surgery and 24 weeks of non-concurrent strength and endurance rehabilitation (with 48 week post-operative follow-up) on (a) subjective (IKDC; KOOS; PP [Chapter 4]) and objective measures of function (HOP [Chapter 5]) (primary outcome measures for this thesis), and (b) objective measures of musculoskeletal (ATFD) and neuromuscular performance (PF, EMD, RFD, SMP
(Chapter 5)) (secondary outcome measures), in patients with anterior cruciate ligament deficiency.” In conclusion, this thesis does provide evidence to support the hypothesis that NCON rehabilitation provides superior functional, musculoskeletal and neuromuscular improvements following ACL reconstruction compared to the traditional CON practice.

7.6 Are there significant relationships amongst the subjective (self-perceived) measure of knee function (IKDC) and objective measures of function (HOP), musculoskeletal (ATFD) and neuromuscular performance (PF, RFD, EMD, SMP) at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery?

In addition to providing evidence as to whether NCON rehabilitation following ACL reconstruction surgery offers superior subjectively- and objectively-measured outcomes compared to the traditional CON rehabilitation, this thesis also evaluated the relationships between the self-perceived (subjective) outcome (IKDC) and the objective measure of functional (HOP), together with the musculoskeletal (ATFD) and neuromuscular measures of performance (PF, RFD, EMD, SMP). The selected relationships were analysed at (i) pre-surgery and at (ii) 24 weeks post-surgery. Pre-surgery was chosen as it addresses the unstable joint, and 24-weeks post-surgery reflects the surgically stabilised knee at the time when the formally structured and supervised ACL rehabilitation had been completed. This is also the time when no clinical restrictions are placed on the patient and at which resumption of full activity and sport starts. Therefore, these two time points might offer insight into
correlations between self-perceived function and objectively-measured function, musculoskeletal and neuromuscular performance in an unstable joint of a deconditioned patient, with that of a stable joint of an optimally rehabilitated patient. Ultimately, if significant relationships were found amongst the array of outcomes currently advocated, then it could potentially lead to the redundancy of one or more of the expensive and time consuming objective assessments. The findings from this evaluation are of great clinical interest in a finance- and time-constrained (NHS) clinical setting.

This section relates to the thesis aim, “To evaluate relationships amongst the subjectively-measured outcome of function (IKDC) and the objectively-measured outcomes of function (HOP), musculoskeletal (ATFD, PF) and neuromuscular (RFD, EMD, SMP) performance at (i) pre-surgery and (ii) 24 weeks post ACL reconstructive surgery and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery.”

Both IKDC and HOP are commonly used in the clinical setting to measure loss or gain and to monitor progression of function (Clark et al. 2001, Gustavsson et al. 2006, Collins et al 2011, Adams et al. 2012, Irrgang et al. 2012). In addition, both are used to establish if a successful outcome to ACL surgery and/or the subsequent rehabilitation has been achieved. Although no consensus exists regarding requirements for a safe return to full function and sport following ACL injury and surgery, both of these outcome measures have been used to offer a degree of confidence in resuming high-demand activities (Shaw et al. 2004, Thomeé et al. 2011). The outcome measures of musculoskeletal and neuromuscular performance in particular are that the assessments have increased cost and time implications for both the institution and the patient. Therefore, if any of these objectively-measured findings
correlated with IKDC, then it could lead to the redundancy or streamlining of the battery of objective tests that are required for future studies, and/ or recommendation of rehabilitation progression and with safe return to full function and sport.

The main RCT’s described in Chapters 4 and 5 provided the population used to evaluate the relationship between IKDC and the objectively-measured outcomes of function (HOP), musculoskeletal (ATFD) and neuromuscular (PF, RFD, EMD, SMP) performance. Although the improvement in rehabilitation addressed in Chapters 4 and 5 was dependent on the mode of rehabilitation (NCON versus CON) \( F_{(2.1, 131.6)} > 4.5; p < 0.01 \), this was small to moderate in absolute effect size (≈5% - 15%). Therefore, this amount was not considered sufficient relative to the population heterogeneity of response, to preclude the amalgamation of data, especially as it would typically offer greater statistical robustness. However, only the data from the NCON and CON groups were amalgamated and computed. (The Limited testing CON group was not assessed at 24 weeks post-surgery).

The relationships analysed involved the absolute scores for the injured leg, injured versus non-injured (contralateral limb) differences and patterns of change were assessed by computing correlation coefficients (Pearson product-moment) between outcome variables IKDC scores and the objectively-measured outcomes (HOP, ATFD, PF, RFD, EMD, SMP) at the pre-surgery and 24 weeks post-surgery assessment occasions. A priori alpha levels were set at \( p < 0.05 \) and two-tailed probabilities were used due to the exploratory nature of this study and as both losses and gains in performance were expected.

The findings demonstrated a limited relationship between two of the primary outcomes of function. This was associated with IKDC and HOP, injured
versus non-injured (contralateral limb) differences at both the pre-surgery and 24 weeks post-surgery assessment occasions ($r = -0.331; p < 0.05$ and $r = -0.258; p < 0.01$, respectively). Though there is statistical significance in this finding, it does not provide any meaningful clinical relevance. This would suggest both the IKDC measure of subjective function and the objective functional outcome HOP reflect different dimensions of function. This finding and conclusion is comparable with previous studies reviewed by Fitzgerald et al. (2001) and Reinke et al. (2011), where correlations ranged from $r = 0.03 – 0.48$.

With respect to neuromuscular performance, the findings did show some statistical correlations which are summarised in Table 7.18.

<table>
<thead>
<tr>
<th>Outcome variables</th>
<th>Test Occasion</th>
<th>Significant Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKDC and RFD ext (absolute scores)</td>
<td>Pre-surgery</td>
<td>0.402</td>
</tr>
<tr>
<td>IKDC and RFD flex (absolute scores)</td>
<td>Pre-surgery</td>
<td>0.404</td>
</tr>
<tr>
<td>IKDC and EMD ext (absolute scores)</td>
<td>Pre-surgery</td>
<td>0.270</td>
</tr>
<tr>
<td></td>
<td>24 weeks post-surgery</td>
<td>-0.296</td>
</tr>
<tr>
<td>IKDC and EMD flex (absolute scores)</td>
<td>Pre-surgery</td>
<td>0.266</td>
</tr>
<tr>
<td></td>
<td>24 weeks post-surgery</td>
<td>-0.321</td>
</tr>
<tr>
<td>IKDC and EMD ext (limb difference)</td>
<td>24 weeks post-surgery</td>
<td>0.313</td>
</tr>
<tr>
<td>IKDC and EMD flex (limb difference)</td>
<td>24 weeks post-surgery</td>
<td>0.379</td>
</tr>
<tr>
<td>IKDC and EMD ext (pattern of change)</td>
<td>24 weeks post-surgery</td>
<td>-0.304</td>
</tr>
<tr>
<td>IKDC and EMD flex (pattern of change)</td>
<td>24 weeks post-surgery</td>
<td>-0.267</td>
</tr>
</tbody>
</table>

Table 7.18 Summary of significant correlation coefficients (Pearson product-moment).
Although these correlation coefficients, ranging from $r = 0.266$ to $0.404$, are statistically significant, they are not robust enough to offer any clinical significance ($r^2 = 0.07$ to $0.16$).

Therefore, only limited and weak to moderate relationships were demonstrated between IKDC and the objectively-measured outcomes of HOP, ATFD, PF, RFD, EMD and SMP whereby each objective outcome variable is independent of the IKDC finding and is contributing separately in the measurement of recovery following ACL surgery and rehabilitation. There is a gap in current research specifically evaluating the relationships between IKDC and neuromuscular performance from which any comparisons of results could be performed. However in contrast to this study, Sernert et al. (1999) did find IKDC correlated with ATFD ($r = -0.34$ to $-0.35$) in a study of 527 post-operative ACL patients at a median of 38 month (21 – 68 months) follow-up. Yet, once again this statistical significance does not imply clinical significance. The results from this study suggest objectively-measured outcomes of function (HOP), musculoskeletal (ATFD) and neuromuscular (PF, RFD, EMD, SMP) performance cannot be predicted by IKDC.

<table>
<thead>
<tr>
<th>Thesis Question</th>
<th>Key Findings</th>
</tr>
</thead>
</table>
| iii) Are there relationships amongst the subjective measure of knee function (IKDC) and objective measures of function (HOP), musculoskeletal (ATFD) and neuromuscular (PF, RFD, EMD and SMP) performance at pre-surgery and 24 weeks post-surgery and amongst the change score between pre-surgery and 24 weeks post ACL reconstructive surgery? | • Limited statistical correlations were found between IKDC and HOP (injured leg versus non-injured [contralateral] leg difference) at pre-surgery and 24 weeks post-surgery (range $r = 0.331$ – $0.330$ $p<0.05$).  
• Limited statistical correlations were found between IKDC and RFD and EMD (range $r = 0.266$ – $0.404$ $p<0.05$).  
• No relationship was found to be clinically relevant.  
• IKDC is independent to all objective outcomes in a clinical scenario. |

Table 7.19 Summary of key findings associated with the thesis aim, to explore relationships amongst subjectively- and objectively-measured outcomes used to assess performance following ACL rehabilitation at pre-surgery, 24 weeks post-surgery and amongst the change scores between pre-surgery and 24 weeks post-surgery.
7.7 Conclusion: Are there significant relationships amongst subjective (self-perceived) measure of knee function (IKDC) and objective measures of function (HOP), musculoskeletal (ATFD) neuromuscular performance (PF, RFD, EMD, SMP) at (i) pre-surgery, (ii) 24 weeks post-surgery, and (iii) amongst the change scores for these outcome measures between pre-surgery and 24 weeks post-surgery?

All the objectively-measured outcomes used to assess functional (HOP), musculoskeletal and neuromuscular performance showed a limited statistical correlation with the self-perceived measurement of function (IKDC). None of these correlations offer any clinical significance. The objectively-measured outcomes cannot be predicted by IKDC, suggesting each of the objective outcomes is measuring a parameter independent of IKDC. Therefore, it would be prudent for any future research projects assessing functional outcomes following knee surgery to use a wide battery of objective and subjective measures.

However, the lack of a clinical significance between the self-perceived (subjective) outcome and the objective outcomes, does have clinical implications. A mis-match between self-perceived and the objective outcomes of function and secondary measures of performance might increase the likelihood of further injury. A patient might perceive they are functioning well enough to return to unrestricted function, but the possible real deficits in musculoskeletal and neuromuscular performance might not be sufficient to be able to withstand the physical demand. Conversely, a patient inadvertently might hold back physical effort within a rehabilitation session through a self-perceived belief that they lack the necessary musculoskeletal and

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neuromuscular fitness. This in turn might lead to a slower progression of physical recovery.

In conclusion, although it is not practical, due to time and financial constraints, for a clinical institution to offer the battery of tests performed in this study, it is advisable that both a patient-reported inventory, like the IKDC, and a simple objective functional test like HOP, be utilised to assess recovery and the possibility of safe return to function.

7.8 Limitations and future research

The logistical and financial costs of a fully-blinded trial were beyond the scope of the PhD programme of research. All patients were treated and assessed by the same physiotherapist for the duration of their rehabilitation period. It had been impossible to fully blind the physiotherapist to the altered characteristics of rehabilitation following surgery, although given the busy nature of the NHS environment, little attention other than that needed to meet basic delivery protocols for the study, had been paid to the participants. Additionally, despite the result of whether NCON delivered superior subjective and objective outcomes compared to the traditional CON rehabilitation, it would still have offered valuable clinical insight. For example, if NCON had not provided improved outcomes or indeed was shown to elicit a detrimental outcome compared to CON rehabilitation, this would still have provided fresh evidence to show the traditional rehabilitation was the most efficacious.

Furthermore, the blinding of patients participating in this study was not possible. This limitation is evident in all of the previous studies investigating NCON versus CON (Chapter 2 – Section – 2.8.5). It would have been obvious to patients if they had been combining heavy resistance exercise with that of CV
endurance within the same session. However, as stated in the patient information sheet [Appendix E], they were fully aware this was an exploratory study and at that time there was no evidence to imply one method of rehabilitation would have provided better outcomes than the other.

Furthermore, the use of a single centre of clinical care at a renowned orthopaedic research U.K. National Health Service Foundation Trust hospital ensured optimal standardisation of care. This might properly be considered an advantage in the context of the delivery of this exploratory trial. However, the ability to extrapolate findings from this study to other NHS environments, joint systems and surgical interventions, would be expected to be limited compared to findings derived from more representative multi-centre trials.

Future studies might, indeed consider delivery of NCON strength and endurance conditioning with a multi-centre comparison to confirm the wider applicability of this study’s exploratory findings. The nature of iso-volumetric rehabilitation amongst the two arms of this study precluded optimised strategies for dosing of strength and endurance exercises within the structured aspect of the programme. This approach might also offer an enhanced potency of NCON intervention and potentially greater effect sizes.

Additionally, it might be advisable that future research investigates the longer-term outcomes and potential re-injury rates following NCON rehabilitation. It would also be of interest if a longer-term study included a continued phasing of NCON exercise beyond the traditional 6 months ACL rehabilitation. It is noteworthy that as self-perception of functional capacity by IKDC was less than that of the normative data at 24 weeks post-surgery, yet patients had been allowed to return to normal function with no restrictions. Indeed IKDC had not returned to being completely normal (i.e. matching pre-
surgery performance capabilities of the non-injured limb), even at the 48 weeks post-surgery assessment occasion. It might be that following a significant injury and subsequent surgery, a patient will never perceive that joint or limb as ‘normal’. In addition, the limb symmetry index associated with HOP is only just over the recommended threshold of 85% for the NCON group by the 48 week assessment occasion. Therefore, these outcomes might suggest rehabilitation has not reached its full potential by 24 weeks and an increased duration of exercise phasing might be beneficial. Furthermore, the application of NCON pre-habilitation and how this might limit deconditioning and provide earlier functional gains would also be insightful.

In summary, this was a novel exploratory study examining NCON rehabilitation out-performed traditional CON rehabilitation using outcome measures applicable to the ACL population. The study was limited by finance and was delivered in a busy NHS physiotherapy department. Therefore, it was not delivered without some limitations, primarily associated with assessor- and patient-blinding and a single-centre environment. Nevertheless, it does add to evidence based medicine and provides a foundation for future research in this area.

7.9 Clinical implications and recommendations for future practice

The findings presented in this research suggest NCON rehabilitation provides superior self-perceived (subjective) and objectively-measured outcomes of functional, musculoskeletal and neuromuscular performance compared to the traditional CON rehabilitation following ACL reconstruction surgery. While there is no definitive conclusion that all the outcomes assessed exceed a minimal clinically important difference, it can be argued that outcome
gains of up to 15% at no extra cost to the institution or patient are clinically significant. Indeed, the hospital where this was performed has adapted rehabilitation packages based on the advantageous results generated by NCON training [Appendix H].

In addition, the advantages of this type of rehabilitation is not isolated to post-operative ACL patients. Upon completion of this thesis, a similar research study using the same methods, but a different patient population has been published and recommends NCON rehabilitation following autologous chondrocyte implantation to knees (Bailey et al. 2014).

Therefore, the clinical implication is that NCON rehabilitation will provide superior gains compared to CON rehabilitation. These results would give credence to the recommendation that post-operative rehabilitation should be prescribed in a NCON format.

7.10 Conclusion of the thesis

This thesis provides evidence that both the traditional CON ACL rehabilitation and the intervention of NCON ACL rehabilitation are efficacious. Both methods provide improvements in both self-perceived and objectively-measured functional, musculoskeletal and neuromuscular outcomes. However, NCON rehabilitation is superior, providing up to a 15% advantage compared to CON. This is in agreement with the majority of the literature investigating the potential for strength attenuation when training concurrently in healthy populations. No previous study was found to have investigated the possibility of improved beneficial gains by rehabilitating in a NCON format in injured or post-operative populations. The findings from this thesis can be applied immediately in a clinical setting, without extra cost.
Additionally, this thesis finds no clinically relevant correlations between subjective outcome of function (IKDC) and objectively-measured outcomes of functional (HOP), musculoskeletal (ATFD) and neuromuscular performance (PF, RFD, EMD and SMP). This suggests in order to provide guidance on rehabilitation progression and on when to potentially return to full function, the deployment of a battery of subjective and objective measures would be prudent.
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Appendix A:

RJAH Anterior Cruciate Ligament

Rehabilitation Guide
### POST-OPERATIVE ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION REGIME
**SPORTS INJURY SURGERY, OSWESTRY.**

<table>
<thead>
<tr>
<th>PHASE OF REHABILITATION</th>
<th>STAGE OF PTG REMODELLING</th>
<th>IDEAL CRITERIA</th>
<th>REHABILITATION GUIDE</th>
<th>GOALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHASE 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 1-Discharge</td>
<td>The graft is at its strongest at this stage, with respect to the soft tissue.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Cryocuff/ Ice.
- Patella mobilisations.
- EOR E mobilisations
- Hamstring (H) and calf stretches.
- Ankle exercises.
- Passive F over edge of bed.
- Static quadriceps (Q).
- Co-contraction Q and H.
- Avoid ‘heavy’ eccentric Q, which may overload the harvest site.
- Prone H, con/ecc/isomet.
- Prone SLR.
- PWB with elbow crutches to comfort.
- Mini squats.
- Heel raises.
- Weight transferring.

1. Reduce inflammation.
2. Gain full terminal E
4. Gradually regain ROM.
5. Introduce early Q/H work.
6. Promote early mobility.
<table>
<thead>
<tr>
<th>PHASE OF REHABILITATION</th>
<th>STAGE OF GRAFT REMODELLING</th>
<th>IDEAL CRITERIA</th>
<th>REHABILITATION GUIDE</th>
<th>GOALS</th>
</tr>
</thead>
</table>
| PHASE 2                 | No initial blood supply to graft, results in avascularisation of the soft tissue aspect. | • Full active and passive E.  
• Mobilise independently +/- aids. | • Static bike no/low resis. as tolerated.  
• Gradually increase weight bearing.  
• Gait re-education (wean off splint and elbow crutches).  
• Low step-touch→step up.  
• Active OKC Q 90°-45°.  
• Progress H work re: Reps/Resis, as able.  
• Other muscle groups not to be neglected. | 1. Promote early function.  
2. Increase ROM.  
3. Encourage weight bearing.  
4. Improve muscular strength/endurance and control. |

Discharge-10 Days
<table>
<thead>
<tr>
<th>PHASE OF REHABILITATION</th>
<th>STAGE OF GRAFT REMODELLING</th>
<th>IDEAL CRITERIA</th>
<th>REHABILITATION GUIDE</th>
<th>GOALS</th>
</tr>
</thead>
</table>
| PHASE 3                  | Avascularisation of graft leads to continual decrease in graft strength. The graft becomes enveloped in a synovial sheath. | Minimal discomfort.  
SLR with no lag.  
AROM = Full E – 100° | FWB.  
Gait with predictable changes in direction.  
Prone auto-overpress F  
develop Q stretch  
Step ups (for/back/sideways)  
height/reps/resis/speed  
Leg press  
reps/resis/speed.  
Early plyometrics.  
Rowing  
dist/speed/resis.  
Progress proprioception  
wobble boards/sit-fit/trampette/crash mats/etc.  
Gym ball, Theraband work  
Hydrotherapy/swimming (AVOID breaststroke legs until 3 month stage)  
Progress general leg exercises VMO, ab/adduction, gluteals, etc.  
Upper body.  
Muscle balance as appropriate.  
Flexibility as appropriate. | 1. Progress functional activities.  
2. Prevent anterior knee pain.  
3. Prevent scar adherence.  
4. Prevent joint stiffness  
5. Restore normal gait pattern.  
6. Promote appropriate muscle strength/power and endurance.  
7. Improve proprioception.  
8. Maintain cardio-vascular fitness.  
<table>
<thead>
<tr>
<th>PHASE OF REHABILITATION</th>
<th>STAGE OF GRAFT REMODELLING</th>
<th>IDEAL CRITERIA</th>
<th>REHABILITATION GUIDE</th>
<th>GOALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHASE 4</td>
<td>Bone blocks unite with surrounding bone and revascularisation of the graft commences. An increase in graft laxity is usually apparent on testing between ~ week 10-12.</td>
<td>'Normal' gait pattern, pain free. Full ROM. 1 leg balance ~1 min.</td>
<td>Progress above as able. Tramette jogging. 'Power' walking → duration/incline/decline/cadence. Isokinetic H.</td>
<td>1. Continue to promote specific function. 2. Increase muscle work and control through range. 3. Isometric Q strength = 75-85%.</td>
</tr>
<tr>
<td>PHASE 5</td>
<td>By month 4 complete revascularisation with the laying down of collagen occurs. A gradual increase in strength is gained as the graft remodels.</td>
<td>30 min. 'Power' walk. Row 2000m within 15 min., mod resis. H ~90% of contra-lateral side. Adequate dynamic proprioception.</td>
<td>Isokinetic Q. OKC Q → reps/resist/speed/con/ ecc/isometric. Plyometrics, drops from 6-18&quot;/bounding, etc. Hopping → stride/direction/stops/speed. Jogging → Running Surface/distance. Progress to incorporate: Agility, run/ sprint/cut/ pivot/ accelerate/ decelerate.</td>
<td>1. Bias to specific function/sport.</td>
</tr>
<tr>
<td>PHASE 6</td>
<td>Dependent on sport. 80-90% isometric and isokinetic Q strength of contra-lateral side. Proprioception ~90% contra-lateral side.</td>
<td>Non-contact training. Non-contact sport.</td>
<td>1. Prepare physical and psychological ability for complete return to unrestricted function.</td>
<td></td>
</tr>
<tr>
<td>PHASE OF REHABILITATION</td>
<td>STAGE OF GRAFT REMODELLING</td>
<td>IDEAL CRITERIA</td>
<td>REHABILITATION GUIDE</td>
<td>GOALS</td>
</tr>
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<td>-------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>PHASE 7</td>
<td>Gradual organisation of collagen. At 1 year the graft resembles the appearance of a ligament with densely organised collagen bundles. The laxity of the graft appears to be linked with muscle strength.</td>
<td>• Symptom free training. • No residual complications. • Psychologically prepared.</td>
<td>• Earliest return to contact sport.</td>
<td>1. Unrestricted confident function.</td>
</tr>
<tr>
<td>From Month 6</td>
<td></td>
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</tbody>
</table>
Appendix B:

International Knee Documentation Committee [IKDC] Subjective Evaluation Form
2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

Your Full Name______________________________________________________

Today’s Date: ______/_______/______                      Date of Injury: __________/________/_____

Day       Month       Year                      Day       Month       Year

SYMPTOMS*:  
*Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?
   - Very strenuous activities like jumping or pivoting as in basketball or soccer
   - Strenuous activities like heavy physical work, skiing or tennis
   - Moderate activities like moderate physical work, running or jogging
   - Light activities like walking, housework or yard work
   - Unable to perform any of the above activities due to knee pain

2. During the past 4 weeks, or since your injury, how often have you had pain?
   - 0 Never
   - 1
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7
   - 8
   - 9
   - 10 Constant

3. If you have pain, how severe is it?
   - 0 No pain
   - 1
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7
   - 8
   - 9
   - 10 Worst pain imaginable

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?
   - Not at all
   - Mildly
   - Moderately
   - Very
   - Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?
   - Very strenuous activities like jumping or pivoting as in basketball or soccer
   - Strenuous activities like heavy physical work, skiing or tennis
   - Moderate activities like moderate physical work, running or jogging
   - Light activities like walking, housework, or yard work
   - Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?
   - Yes
   - No

7. What is the highest level of activity you can perform without significant giving way in your knee?
   - Very strenuous activities like jumping or pivoting as in basketball or soccer
   - Strenuous activities like heavy physical work, skiing or tennis
   - Moderate activities like moderate physical work, running or jogging
   - Light activities like walking, housework or yard work
   - Unable to perform any of the above activities due to giving way of the knee
SPORTS ACTIVITIES:

8. What is the highest level of activity you can participate in on a regular basis?
- Very strenuous activities like jumping or pivoting as in basketball or soccer
- Strenuous activities like heavy physical work, skiing or tennis
- Moderate activities like moderate physical work, running or jogging
- Light activities like walking, housework or yard work
- Unable to perform any of the above activities due to knee

<table>
<thead>
<tr>
<th>9. How does your knee affect your ability to:</th>
<th>Not difficult at all</th>
<th>Minimally difficult</th>
<th>Moderately Difficult</th>
<th>Extremely difficult</th>
<th>Unable to do</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Go up stairs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Go down stairs</td>
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<tr>
<td>c. Kneel on the front of your knee</td>
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<tr>
<td>d. Squat</td>
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<td></td>
</tr>
<tr>
<td>e. Sit with your knee bent</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f. Rise from a chair</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>g. Run straight ahead</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>h. Jump and land on your involved leg</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i. Stop and start quickly</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

FUNCTION:

9. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

FUNCTION PRIOR TO YOUR KNEE INJURY:

<table>
<thead>
<tr>
<th>Cannot perform daily activities</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>No limitation in daily activities</th>
</tr>
</thead>
<tbody>
<tr>
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<td>☐</td>
<td></td>
</tr>
</tbody>
</table>

CURRENT FUNCTION OF YOUR KNEE:

<table>
<thead>
<tr>
<th>Cannot perform daily activities</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>No limitation in daily activities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>
Scoring Instructions for the 2000 IKDC Subjective Knee Evaluation Form

Several methods of scoring the IKDC Subjective Knee Evaluation Form were investigated. The results indicated that summing the scores for each item performed as well as more sophisticated scoring methods.

The responses to each item are scored using an ordinal method such that a score of 1 is given to responses that represent the lowest level of function or highest level of symptoms. For example, item 1, which is related to the highest level of activity without significant pain is scored by assigning a score of 1 to the response “Unable to Perform Any of the Above Activities Due to Knee” and a score of 5 to the response “Very strenuous activities like jumping or pivoting as in basketball or soccer”. For item 2, which is related to the frequency of pain over the past 4 weeks, the response “Constant” is assigned a score of 1 and “Never” is assigned a score of 11.

The IKDC Subjective Knee Evaluation Form is scored by summing the scores for the individual items and then transforming the score to a scale that ranges from 0 to 100. Note: The response to item 10 “Function Prior to Knee Injury” is not included in the overall score. The steps to score the IKDC Subjective Knee Evaluation Form are as follows:

1. Assign a score to the individual’s response for each item, such that lowest score represents the lowest level of function or highest level of symptoms.
2. Calculate the raw score by summing the responses to all items with the exception of the response to item 10 “Function Prior to Your Knee Injury”
3. Transform the raw score to a 0 to 100 scale as follows:

   \[
   \text{IKDC Score} = \left[ \frac{\text{Raw Score} - \text{Lowest Possible Score}}{\text{Range of Scores}} \right] \times 100
   \]

   Where the lowest possible score is 18 and the range of possible scores is 87. Thus, if the sum of scores for the 18 items is 60, the IKDC Score would be calculated as follows:

   \[
   \text{IKDC Score} = \left[ \frac{60 - 18}{87} \right] \times 100
   \]

   IKDC Score = 48.3

The transformed score is interpreted as a measure of function such that higher scores represent higher levels of function and lower levels of symptoms. A score of 100 is interpreted to mean no limitation with activities of daily living or sports activities and the absence of symptoms.

The IKDC Subjective Knee Score can still be calculated if there are missing data, as long as there are responses to at least 90% of the items (i.e. responses have been provided for at least 16 items). To calculate the raw IKDC score when there are missing data, substitute the average score of the items that have been answered for the missing item score(s). Once the raw IKDC score has been calculated, it is transformed to the IKDC Subjective Knee Score as described above.
Appendix C:

Knee Injury and Osteoarthritis Outcome

Score (KOOS)
KOOS KNEE SURVEY

Today’s date: _____/_____/______ Date of birth: _____/_____/______

Name: ____________________________________________________

INSTRUCTIONS: This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to do your usual activities. Answer every question by ticking the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms
These questions should be answered thinking of your knee symptoms during the last week.

S1. Do you have swelling in your knee?

<table>
<thead>
<tr>
<th>Never</th>
<th>Rarely</th>
<th>Sometimes</th>
<th>Often</th>
<th>Always</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

<table>
<thead>
<tr>
<th>Never</th>
<th>Rarely</th>
<th>Sometimes</th>
<th>Often</th>
<th>Always</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

S3. Does your knee catch or hang up when moving?

<table>
<thead>
<tr>
<th>Never</th>
<th>Rarely</th>
<th>Sometimes</th>
<th>Often</th>
<th>Always</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

S4. Can you straighten your knee fully?

<table>
<thead>
<tr>
<th>Always</th>
<th>Often</th>
<th>Sometimes</th>
<th>Rarely</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

S5. Can you bend your knee fully?

<table>
<thead>
<tr>
<th>Always</th>
<th>Often</th>
<th>Sometimes</th>
<th>Rarely</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
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</tbody>
</table>

Stiffness
The following questions concern the amount of joint stiffness you have experienced during the last week in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your knee joint stiffness after first wakening in the morning?

<table>
<thead>
<tr>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

S7. How severe is your knee stiffness after sitting, lying or resting later in the day?

<table>
<thead>
<tr>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
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<td>☐</td>
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<td>☐</td>
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</tbody>
</table>
**Pain**

P1. How often do you experience knee pain?
- Never
- Monthly
- Weekly
- Daily
- Always

What amount of knee pain have you experienced the last week during the following activities?

P2. Twisting/pivoting on your knee
- None
- Mild
- Moderate
- Severe
- Extreme

P3. Straightening knee fully
- None
- Mild
- Moderate
- Severe
- Extreme

P4. Bending knee fully
- None
- Mild
- Moderate
- Severe
- Extreme

P5. Walking on flat surface
- None
- Mild
- Moderate
- Severe
- Extreme

P6. Going up or down stairs
- None
- Mild
- Moderate
- Severe
- Extreme

P7. At night while in bed
- None
- Mild
- Moderate
- Severe
- Extreme

P8. Sitting or lying
- None
- Mild
- Moderate
- Severe
- Extreme

P9. Standing upright
- None
- Mild
- Moderate
- Severe
- Extreme

**Function, daily living**

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the last week due to your knee.

A1. Descending stairs
- None
- Mild
- Moderate
- Severe
- Extreme

A2. Ascending stairs
- None
- Mild
- Moderate
- Severe
- Extreme
For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

<table>
<thead>
<tr>
<th>Activity</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3. Rising from sitting</td>
<td></td>
<td></td>
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<tr>
<td>A4. Standing</td>
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<tr>
<td>A5. Bending to floor/pick up an object</td>
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<tr>
<td>A6. Walking on flat surface</td>
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<tr>
<td>A7. Getting in/out of car</td>
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<tr>
<td>A8. Going shopping</td>
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<tr>
<td>A9. Putting on socks/stockings</td>
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<tr>
<td>A10. Rising from bed</td>
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<tr>
<td>A11. Taking off socks/stockings</td>
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<tr>
<td>A12. Lying in bed (turning over, maintaining knee position)</td>
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</tr>
<tr>
<td>A13. Getting in/out of bath</td>
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</tr>
<tr>
<td>A14. Sitting</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>A15. Getting on/off toilet</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
For each of the following activities please indicate the degree of difficulty you have experienced in the last week due to your knee.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc.)
None        Mild        Moderate        Severe        Extreme

A17. Light domestic duties (cooking, dusting, etc.)
None        Mild        Moderate        Severe        Extreme

**Function, sports and recreational activities**
The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the last week due to your knee.

SP1. Squatting
None        Mild        Moderate        Severe        Extreme

SP2. Running
None        Mild        Moderate        Severe        Extreme

SP3. Jumping
None        Mild        Moderate        Severe        Extreme

SP4. Twisting/pivoting on your injured knee
None        Mild        Moderate        Severe        Extreme

SP5. Kneeling
None        Mild        Moderate        Severe        Extreme

**Quality of Life**

Q1. How often are you aware of your knee problem?
Never        Monthly        Weekly        Daily        Constantly

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?
Not at all        Mildly        Moderately        Severely        Totally

Q3. How much are you troubled with lack of confidence in your knee?
Not at all        Mildly        Moderately        Severely        Extremely

Q4. In general, how much difficulty do you have with your knee?
None        Mild        Moderate        Severe        Extreme

Thank you very much for completing all the questions in this questionnaire.
Appendix D:

Tabular Description of the Literature

Associated with Non-Concurrent versus Concurrent Training (Including Cohen’s $d$
and PEDro score) with respect to Neuromusculoskeletal Outcomes
<table>
<thead>
<tr>
<th>No.</th>
<th>Author (year)</th>
<th>Training Subjects (Age)</th>
<th>Training Groups</th>
<th>Volume and intensity of training</th>
<th>Performance indicator</th>
<th>Statistically significant results and applicable to this thesis (if available for Cohen's $d$ effect size calculation)</th>
<th>Pedro score</th>
<th>Is strength attenuated?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Karavirta et al. 2011</td>
<td>105 untrained men (mean age 56±7 years)</td>
<td>S / E / SE / C</td>
<td>21 weeks training intervention:</td>
<td>Tested 2 weeks pre- and week 10 of training intervention and post- at week 21.</td>
<td>Only % changes referred to in body of test and figures for maximal isometric leg press and bench press; maximal dynamic strength, concentric power, maximal EMG VM and VL; maximal oxygen consumption and aerobic cycling power; CSA of muscle fibres type I and II.</td>
<td>5/10</td>
<td>Yes</td>
</tr>
</tbody>
</table>
|     |               | 96 complete study.      |                 | S (n = 25)                        | Aerobic performance.  | **Legend:**
|     |               |                        |                 | 2 x wk.                          | Strength and Power:  | **Note:**
|     |               |                        |                 | Leg press.                       | 1 RM leg press.       | -
|     |               |                        |                 | Leg extension.                   | Isometric bilateral leg extension. |
|     |               |                        |                 | Knee curl.                       | Isometric bench press.|
|     |               |                        |                 | Seated calf raise.               | EMG: VL, VM, TB.      |
|     |               |                        |                 | Hip adduction or abduction.      | Muscle biopsies:     |
|     |               |                        |                 | Bench press.                     | Fibre type and CSA   |
|     |               |                        |                 | Biceps curl.                     | (S n = 11: , n = 7: SE n = 12: C n = 3): |
|     |               |                        |                 | Triceps push-down.               | Blood samples:       |
|     |               |                        |                 | Lateral pull down.               | Testosterone.         |
|     |               |                        |                 | Abdominal crunch.                | Cortisol             |
|     |               |                        |                 | Seated back extension.           |                     |
|     |               |                        |                 | **Notes:**                        |                     |
|     |               |                        |                 | **Week 1 – 7**                    |                     |
|     |               |                        |                 | 3 sets at 40 – 60% of 1 RM,      |                     |
|     |               |                        |                 | 12 – 20 reps.                    |                     |
|     |               |                        |                 | **Weeks 8 – 14**                 |                     |
|     |               |                        |                 | 2 – 4 sets at 60 – 80% of 1 RM,  |                     |
|     |               |                        |                 | 5 – 12 reps.                     |                     |
|     |               |                        |                 | **Weeks 15 – 21**                |                     |
|     |               |                        |                 | 2 – 4 sets at 70 – 85% of 1 RM,  |                     |
|     |               |                        |                 | 5 – 8 reps.                      |                     |
|     |               |                        |                 | 20% of leg press, knee extension and bench press at 40 -50% of 1 RM, explosive strength. |                     |
|     |               |                        |                 | E (n = 25)                        |                     |
|     |               |                        |                 | 2 x wk.                          |                     |
Week 1 – 7
30-min cycle ergometer, below aerobic threshold.

Weeks 5 – 7
3 x 10-min, middle 10-min above aerobic threshold.

Weeks 8 – 14
Session 1:
45-min-total
15-min warm-up below aerobic threshold,
10-min interval between aerobic-anaerobic thresholds,
5-min above anaerobic threshold,
15-min cool-down below aerobic threshold.
Session 2:
60-min cycle below aerobic threshold.

Weeks 15 – 21
Session 1:
60-min-total.
2 x 10-min intervals between anaerobic and aerobic thresholds, 2 x 5-min intervals above aerobic threshold, 30-min below aerobic threshold.
Session 2:
90-min cycle below aerobic threshold

SE (n = 30)
4 x wk, combining S and E
training, as above. Sequencing is not described.

| C (n = 16) |
|------------|------------------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|

<table>
<thead>
<tr>
<th>2</th>
<th>Cadore et al. 2010</th>
<th>23 men (65±4 years)</th>
<th>S / E / SE</th>
<th>12 weeks training intervention</th>
<th>Tested twice before training at 4 weeks prior and at the start of the training intervention and at week 12.</th>
<th>S</th>
<th>5/10</th>
<th>Yes</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>3 x wk, non-consecutive days:</td>
<td>Body Composition.</td>
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<td>S (n = 8)</td>
<td>Inclined leg press.</td>
<td>Aerobic capacity:</td>
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<td>Knee extension.</td>
<td>VO\textsubscript{2}\text{peak}</td>
<td>↓ EMG VL 40% (d = 1.06)</td>
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<td>Leg curl.</td>
<td>VT\textsubscript{2}</td>
<td>↓ EMG VL 60% (d = 1.15)</td>
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<td>Free-weight bench press.</td>
<td>HR\text{VT}</td>
<td>↓ EMG VL 80% (d = 1.71)</td>
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<td>Lat pull-down.</td>
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<td>Seated row.</td>
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<td>Triceps curl.</td>
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<td>Free-weight biceps curl.</td>
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<td></td>
<td>Abdominal exercises.</td>
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<td>Stretches and 1 x 25 reps very light loads were used as a warm-up.</td>
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<td>Week 1</td>
<td>3 training days</td>
<td>Maximal dynamic strength:</td>
<td>E</td>
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<td></td>
<td>2 sets of 18 – 20 RM</td>
<td>1 RM bench press and bilateral knee extension.</td>
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<td>Week 2</td>
<td>Maximal isometric strength:</td>
<td>SE</td>
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<td></td>
<td>2 training days</td>
<td>Knee extension</td>
<td>↓ Lower body 1RM (d = 0.96)</td>
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<td></td>
<td>2 sets of 18 – 20 RM</td>
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<td>Free testosterone (d = 0.62)</td>
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<td>Week 3 - 4</td>
<td>Blood samples:</td>
<td>E</td>
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<td>3 training days</td>
<td>Total testosterone</td>
<td>↓ Lower body 1RM (d = 2.39)</td>
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<td>2 sets of 15 – 17 RM</td>
<td>Free testosterone Cortisol</td>
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</tbody>
</table>
Weeks 11 – 12
3 training days
3 sets 6 – 8 RM

90-120-sec rest between sets

E (n = 7)
Week 1
3 training days
20-min cycle at 80% of $HR_{VT}$

Week 2
2 training days
20-min cycle at 80% of $HR_{VT}$

Week 3
3 training days
20-min cycle at 85% of $HR_{VT}$

Week 4 – 5
3 training days
25-min cycle at 85% of $HR_{VT}$

Week 6
3 training days
25-min cycle at 90% of $HR_{VT}$

Week 7- 8
3 training days
30-min cycle at 90% of $HR_{VT}$

Week 9 - 10
3 training days
30-min cycle at 95% of $HR_{VT}$

Week 11 – 12
3 training days
6 x 4-min/ cycle, 1-min resting
SE (n = 8)
Combined volume of S and E training. S preceded E. Each session lasted approx. 70-min.

<table>
<thead>
<tr>
<th>3</th>
<th>Santtila et al. 2009</th>
<th>72 military conscripts (19.2 ±0.9 years)</th>
<th>BT/ BTE / BTS</th>
<th>8 weeks training intervention:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Basic Training (BT) (n = 24)</td>
<td>Total of 300-h military training.</td>
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<td>Combat/ marching; carried 15 – 25 kg load at aerobic level.</td>
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<td>Shooting.</td>
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<td>Material handling.</td>
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<td>Skill training</td>
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<td></td>
<td>Sport/ physical training 12-h-wk; Ball games, orienteering, other sports activities/ running, Nordic walking, walking, cycling. (Total 33-h)</td>
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<td>BTS (n = 24)</td>
<td>Sport/ physical training was replaced with;</td>
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<td>3 x wk strength sessions 60 – 90-m (total 44-h):</td>
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<td>Gym training.</td>
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<td>Circuit training</td>
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<td>Weeks 0 – 3</td>
<td>2 – 3 sets of 10 – 15 or 20 -40 reps at 30 – 5-0% or 60 -70% of 1RM</td>
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<td>Weeks 4 – 5</td>
<td>2 – 4 sets of 6 – 10 reps at 60 – 80% of 1RM</td>
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<td>Tested pre- and post-intervention. [0 – 8 wks]</td>
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<td>Isometric force time curves.</td>
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<td>Max isometric force.</td>
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<td>RFD</td>
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<td>EMG: VL, VM, RF, TB.</td>
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<td>Muscle thickness right VL, VM, TB.</td>
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<td>Anthropometry: % fat measured by skin fold thickness and BMI.</td>
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<td>Aerobic capacity: VO2 max</td>
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<td>Only % data used in text.</td>
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<td>From figures:</td>
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<td>BTS Bilateral arm extensors max RFD (d = 0.31)</td>
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<td>Right arm extensors average EMG; 0 – 500 –ms (d = 0.52)</td>
<td>500 – 1500-ms (d = 0.47)</td>
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<td>BTE Right arm extensors average EMG; 0 – 500 –ms (d = 0.74)</td>
<td>500 – 1500-ms (d = 0.54)</td>
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<td></td>
<td>All other data was not significant or documented in %</td>
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</tbody>
</table>

5/10 Yes
**Weeks 6 – 8**  
5 – 7 sets of 1 – 6 reps at 80 – 100% of 1RM  
Explosive strength at 30-50% 1RM

BTE (n = 24)  
Sport/ physical training was replaced with;  
3 x endurance sessions of 60 -90-m of Nordic walking, walking, running, bicycling and ‘other’ endurance exercises, performed mainly at the aerobic level. (Total of 51-h).

<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Design</th>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
<th>Session 4</th>
<th>Session 5</th>
<th>Session 6</th>
<th>Session 7</th>
<th>Test</th>
<th>Changes</th>
<th>Pre-post Changes</th>
</tr>
</thead>
</table>
| Glowacki et al. 2004 | 45 untrained men | S (23±3 years), E (25±5 years), SE (22±2 years) | 12 weeks training intervention [one additional week (week 7) used for mid-training retesting.] | S (n=13)  
Week 1 & 2  
1x 10 reps (50% 1RM)  
3 x 10 reps (75% 1RM)  
Week 3 & 4  
1x 10 reps (50% 1RM)  
3 x 8 reps (80% 1RM)  
Week 5 & 6  
1x 10 reps (50% 1RM)  
3 x 6 reps (85% 1RM)  
Week 8 & 9  
1x 10 reps (50% 1RM)  
3 x 10 reps (75% 1RM) | Tested pre-, mid- and post-training intervention.  
Strength:  
Isokinetic peak torque production and average power for knee flexion and extension at speeds of 60 and 180°.s⁻¹  
1RM for leg press and barbell.  
Functional:  
Vertical Jump Height  
Aerobic capacity:  
VO₂peak  
Body Weight | S | ↑ Body weight pre- to mid-testing (d = 0.15)  
↑ Lean body mass pre- to mid-testing (d =0.18)  
↑ Jump power pre- to mid-testing (d = 0.20) and pre- to post testing (d = 0.03)  
↑ 1 RM leg press pre- to mid-testing (d = 0.90) and pre- to post testing (d = 1.63)  
↑ 1 RM bench press pre- to mid-testing (d = 0.58) and pre- to post testing (d =1.05)  
↑ Peak torque extension (180°.s⁻¹) pre- to post-testing (d = 0.41)  
↑ average power flexion (60°.s⁻¹) pre- to post-testing (d = 0.44)  
↑ Peak torque flexion (180°.s⁻¹) pre- to post-testing (d = 0.47) | E | ↑ VO₂peak (L.min⁻¹) pre- to mid-testing (d = 0.33) | 5/10 | No |
Week 10 & 11
1x 10 reps (50% 1RM)
3 x 8 reps (80% 1RM)

Week 12 & 13
1x 10 reps (50% 1RM)
3 x 6 reps (85% 1RM)

2x wk\(^{-1}\) every odd numbered week and 3 x wk\(^{-1}\) every even numbered week.

E (n=12)
Each session started with muscle warm-up and stretching.

Week 1 & 2
20-min at 65% of HRR

Week 3 & 4
25-min at 70% of HRR

Week 5 & 6
30-min at 70% of HRR

Week 8 & 9
35-min at 75% of HRR

Week 10 & 11
40-min at 75% of HRR

Week 12 & 13
40-min at 80% of HRR

\(\uparrow \text{VO}_{\text{peak}} \text{ (mL.kg}^{-1}.\text{min}^{-1}\)) \text{ pre- to mid-testing (}d = 0.30\)
\(\downarrow \% \text{ Body fat pre- to post-testing (}d = 0.15\)
\(\uparrow \text{ 1 RM leg press pre- to mid-testing (}d = 0.36\) and pre- to post testing (}d = 0.94\)
\(\uparrow \text{ 1 RM bench press pre- to post testing (}d = 0.28\)
\(\uparrow \text{ Peak torque extension (}180^\circ.\text{s}^{-1}\)) \text{ pre- to post-testing (}d = 0.29\)

SE
\(\uparrow \text{ Body weight pre- to post-testing (}d = 0.09\)
\(\downarrow \% \text{ Body fat pre- to mid-testing (}d = 0.15\)
\(\uparrow \text{ Lean body mass pre- to mid-testing (}d = 0.22\)
\(\uparrow \text{ 1 RM leg press pre- to mid-testing (}d = 1.00\) and pre- to post testing (}d = 1.68\)
\(\uparrow \text{ 1 RM bench press pre- to mid-testing (}d = 0.57\) and pre- to post testing (}d = 0.92\)
SE (n=16)
Trained 5x wk\(^{-1}\) in total.
Every odd numbered week as the S group 3 x week and the E group 2 x week and 3x wk\(^{-1}\). Every even numbered week trained as the E group 3 x per week and the S group 2 x per week.

<table>
<thead>
<tr>
<th>5</th>
<th>Kraemer et al. 2004</th>
<th>35 male soldiers</th>
<th>S / E / SE/ upper-SE</th>
<th>12 week training intervention 4 x wk (M, T, T, F):</th>
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<tbody>
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<td></td>
<td>S</td>
<td>E</td>
<td>SE</td>
<td>S</td>
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<tr>
<td></td>
<td>(24.3±3.6 years)</td>
<td>(21.4.3±1.4 years)</td>
<td>(23.3±3.6 years)</td>
<td>2 x wk</td>
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<td>5 x 5 RM (rest 2 – 3.min)</td>
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<td></td>
<td>Bench press</td>
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<td>Shoulder press</td>
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<td>Biceps curl</td>
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<td>Lat pull-down</td>
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<td>4 x 6 RM (rest 2 – 3.min)</td>
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<td>Dead lift</td>
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<td>5 x 5 RM (rest 2 – 3.min)</td>
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<td>Leg press</td>
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<td>Leg extension</td>
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<td>3 x 10 RM (rest 2 – 3.min)</td>
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<td>Calf raises</td>
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<td>5 x 10 RM</td>
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<td>Obliques</td>
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<td>Sit-ups</td>
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<td>2 x wk</td>
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<td>3 x 10 RM (rest 1.min)</td>
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<td>Bench press &amp; chest fly’s</td>
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<td>2 x 10 RM (rest 1.min)</td>
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<td>Shoulder press &amp; seated row</td>
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<td>3 x 10 RM (rest 1.min)</td>
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<td>Biceps curls</td>
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<td>Single leg extension &amp; leg</td>
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<td>Tested pre- and post-training intervention.</td>
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<td>Max push-ups in 2.min</td>
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<td>Max sit-ups in 2.min</td>
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<td>2 mile run (unloaded) speed.</td>
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<td>2 mile loaded run speed, HR and RPE</td>
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<td>Body composition.</td>
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<td>Max effort countermovement jump.</td>
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<td>Body composition.</td>
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<td>↑ Max push-ups (d = 2.06)</td>
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<td>↑ Max sit-ups (d = 3.18)</td>
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<td>↑ vertical jump height (d = 0.63)</td>
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<td>↑ Fat free mass (d = 0.31)</td>
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<td>↓ % Body fat (d = 0.43)</td>
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<td>↑ Max push-ups (d = 0.62)</td>
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<td>↑ Max sit-ups (d = 0.95)</td>
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<td>↑ 2-mile run speed (d = 0.84)</td>
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<td>↑ Max push-ups (d = 1.13)</td>
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<td>↑ Max push-ups (d = 1.96)</td>
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<td>↑ Max sit-ups (d = 1.59)</td>
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<td>↑ 2-mile run speed (d = 0.87)</td>
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<td>↑ vertical jump height (d = 0.99)</td>
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<td>↑ Fat free mass (d = 0.41)</td>
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<td>↑ % Body fat (d = 0.59)</td>
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<td>↑ Max push-ups (d = 1.13)</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>E</td>
<td>SE</td>
<td>upper-SE</td>
</tr>
</tbody>
</table>

**Tested pre- and post-training intervention.**
curl
Split squats
3 x 15 RM (rest 1 min)
Calf raises
2 x 25 RM (rest 1 min)
Sit-ups

E
2 x wk.
Long distance run, running as far as possible in 40 min., maintaining 70-80% VO\textsubscript{2} max.

2 x wk
Sprint interval training, 100 – 400m, sprint intervals 400-800m, exercise: rest = 1:4 to 1:0.5. 90-100% VO\textsubscript{2} max

SE
E morning/ (5 – 6 hours rest)
S afternoon

Upper-SE
E morning / (5 – 6 hours rest)
S afternoon

---

<table>
<thead>
<tr>
<th>6</th>
<th>Häkkinen et al. 2003</th>
<th>32 males (5 withdrew after first measurements or during the study)</th>
<th>S / SE</th>
<th>22 weeks training intervention [week 1 acting as a control period].</th>
<th>S (n = 16) 2 x wk: Bilateral leg press and/or unilateral knee extension exercise using a dynamometer. Bench press and/or triceps pushdown and/or lateral pull down.</th>
<th>Tested on 5 occasions: -1/ 0/ 7/ 14/ 12 weeks pre-, post and during training intervention. -1 – week 1 [acting as a control period]</th>
<th>S</th>
<th>3/10</th>
<th>No</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>† Bilateral leg extension 1RM (d = 0.38)</td>
<td>† Max IEMG right VL; 0 – 7 wk (d = 0.49) 0 – 14 wk (d = 0.84) 0 – 21 wk (d = 0.74)</td>
<td>† Max IEMG left VL; 0 – 7 wk (d = 0.15) 0 – 14 wk (d = 0.39) 0 – 21 wk (d = 0.28)</td>
</tr>
</tbody>
</table>
Sit-ups and/or trunk extensor exercise.
Bilateral/unilateral elbow and/or knee flexion exercise and/or leg adduction/abduction exercise.

Week 2 – 7 = 2-3 sets of 10-15 reps at 50% - 70% of 1RM
Leg extensor exercises; 3 – 5 sets of either 8 – 12 reps per set or 5-6 reps per set.

Week 8 – 21
50% - 60% - and 60% - 80% of 1RM
(Weeks 15 – 21) Leg extensor exercises; 3 – 5 sets of 3 – 6 reps per set at 70% - 80% of 1RM and 8 – 12 reps per set at 50% - 60% of 1RM

SE (n = 11)
4 x wk.

2 x wk as S group with the addition of a further two training days within the week.

Week 2 – 7
30-min cycle or walking (under aerobic threshold)

Week 8 – 14
1 x wk: 45-min; 15-min below aerobic thresholds, 10-min between aerobic-anaerobic thresholds, 5-min above

EMG: VL (bilateral) and BF (right leg only, as it acts as an antagonist during isometric knee extension).

Muscle CSA: Right QF using MRI.

Muscle biopsies of right VL to classify fibre type.

VO₂ max

Anthropometry: % fat measured by skin fold thickness.

\[ \text{SE} \downarrow \% \text{ Body fat; } \]
\[ 0 - 7 \text{ wk (} d = 0.06 \) \]
\[ 0 - 14 \text{ wk (} d = 0.08 \) \]
\[ 0 - 21 \text{ wk (} d = 0.16 \) \]

\[ \uparrow \text{ Bilateral leg extension 1RM (} d = 0.17 \) \]

\[ \uparrow \text{ Max IEMG right VL; } \]
\[ 0 - 7 \text{ wk (} d = 0.45 \) \]
\[ 0 - 14 \text{ wk (} d = 0.23 \) \]
\[ 0 - 21 \text{ wk (} d = 0.25 \) \]

\[ \text{VO}_2 \text{ max } \]
\[ 0 - 7 \text{ wk (} d = 0.70 \) \]
\[ 0 - 14 \text{ wk (} d = 1.00 \) \]
\[ 0 - 21 \text{ wk (} d = 1.11 \) \]
anaerobic threshold and 15-min under aerobic threshold.
1 x wk: 60-min under aerobic threshold.

Week 15 – 22
1 x wk: 60-min; 15-min under aerobic threshold, 2 x 10-min between the aerobic – anaerobic thresholds, 2 x 5-min above the anaerobic threshold and 15-min under aerobic threshold.
1 x wk: 60-90-min under aerobic threshold.

| 7 | Leveritt et al. 2003 | 11 men S / E/ SE | 6 weeks training intervention [3 x wk. (M,W, F)] S (n = 8; 5 ♂ 3 ♀) 3 sets at 8, 6 and 4 RM Half squat 3 sets 10, 8 and 6 RM Leg extension Hamstring curl Bench press Lat pull-down Biceps curl Lateral raises Abdominal crunches 3 – 4-min rest between reps and sets. E (n = 9; 3 ♂ 6 ♀) 5-min bouts of cycling: 5-min rest 5-min bout work rates = successive 1-mins at 40 – 60 | Tested pre- and post-training intervention. | S | ↑ 1 RM squat S > E (d = 1.77) ↑ 1 RM squat S > SE (d = 0.40) Strength: Isonertial 1 RM squat Isometric knee extension Isokinetic (1.04, 3.12, 5.20, 8.67 rad.s⁻¹) E ↑ VO₂ peak E > S (d = 0.41) SE Aerobic capacity: VO₂ peak Wingate test | 6/10 | No |
8 Balabinis et al. 2003

<table>
<thead>
<tr>
<th>26 male basketball players. ('college age')</th>
<th>S / E / SE/ C</th>
<th>7 weeks training intervention: Tested pre- and post-training intervention).</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (n = 7)</td>
<td></td>
<td>Power and speed: Vertical jump Wingate test Strength: Half squats 1 RM Bench press 1 RM</td>
</tr>
<tr>
<td>4 x wk. 7 weeks</td>
<td></td>
<td>Leg press 1 RM Lat pull-down 1 RM</td>
</tr>
<tr>
<td>Week 1</td>
<td></td>
<td>Aerobic capacity: VO_2_{max}</td>
</tr>
<tr>
<td>Half squat</td>
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<tr>
<td>2 x 6 reps at 75% of 1 RM</td>
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<td>1 x 4 reps at 80% of 1 RM</td>
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<tr>
<td>Bench press</td>
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<tr>
<td>2 x 6 reps at 80% of 1 RM</td>
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<td></td>
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<tr>
<td>1 x 4 reps at 85% of 1 RM</td>
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<tr>
<td>Leg press</td>
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<td></td>
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<tr>
<td>2 x 6 reps at 75% of 1 RM</td>
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<tr>
<td>1 x 4 reps at 80% of 1 RM</td>
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<tr>
<td>Lat pull-down</td>
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<tr>
<td>2 x 6 reps at 80% of 1 RM</td>
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<td>1 x 4 reps at 85% of 1 RM</td>
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<tr>
<td>Week 2</td>
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<tr>
<td>Half squat</td>
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<td></td>
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<tr>
<td>2 x 5 reps at 85% of 1 RM</td>
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<tr>
<td>4 x 4 reps at 90% of 1 RM</td>
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<tr>
<td>Bench press</td>
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<td>2 x 5 reps at 85% of 1 RM</td>
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<tr>
<td>3 x 4 reps at 90% of 1 RM</td>
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<tr>
<td>Leg press</td>
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<tr>
<td>2 x 5 reps at 85% of 1 RM</td>
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<tr>
<td>4 x 4 reps at 90% of 1 RM</td>
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<tr>
<td>Lat pull-down</td>
<td></td>
<td></td>
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<tr>
<td>2 x 5 reps at 85% of 1 RM</td>
<td></td>
<td></td>
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<tr>
<td>4 x 4 reps at 90% of 1 RM</td>
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<tr>
<td>VO_2_{peak}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SE (n = 8; 3 ♂ 6 ♀) E always preceding S</td>
<td></td>
<td></td>
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<tr>
<td>5/10 No</td>
<td></td>
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</tr>
</tbody>
</table>

Vertical jump: (d = 2.42) Wingate test: (d = 0.41) VO_2_{max}: (d = 1.95)
Results documented % changes for statistically significant improvement in 1 RM efforts, but unable to define d value.

% Body fat: (d = 0.85) Body weight: (d = 1.6)
Statistical difference given in % only for

Vertical jump: (d = 2.27) Wingate test: (d = 0.77) VO_2_{max}: (d = 4.75)
Results documented % changes for statistically significant improvement in 1 RM efforts, but unable to define d value.

No statistical differences found.
2 x 4 reps at 90% of 1 RM
2 x 3 reps at 95% of 1 RM
Bench press
2 x 4 reps at 90% of 1 RM
1 x 4 reps at 95% of 1 RM
Leg press
2 x 4 reps at 90% of 1 RM
2 x 3 reps at 95% of 1 RM
Lat pull-down
2 x 4 reps at 90% of 1 RM
1 x 4 reps at 95% of 1 RM

Week 4
Half squat
4 x 6 reps at 70% of 1 RM
Bench press
5 x 5 reps at 70% of 1 RM
Leg press
4 x 6 reps at 70% of 1 RM
Lat pull-down
5 x 5 reps at 70% of 1 RM
Plyometrics;
Front cone hops
Tuck jump
Incline depth push-up
2 x 15 reps/ 2-min rest

Week 5
Half squat
4 x 8 reps at 70% of 1 RM
Bench press
5 x 7 reps at 70% of 1 RM
Leg press
4 x 8 reps at 70% of 1 RM
Lat pull-down
5 x 7 reps at 70% of 1 RM
Plyometrics;
Front cone hops
Tuck jump
Incline depth push-up
2 x 15 reps/ 2-min rest

Week 6
Half squat
Bench press
Leg press
Lat pull-down
3 x 30 reps at 40% of 1 RM

Week 7
Half squat
Bench press
Leg press
Lat pull-down
3 x 40 reps at 40% of 1 RM

E (n = 7)
4 x wk. 7 weeks
Week 1
5-mile at 70% HRmax

Week 2
8.200.m (stride/ 1.5-min interval)
8.100.m (stride/ 45-sec interval)
8.200.m (stride/ 1.5-min interval)
8.100.m (stride/ 45-sec interval)

Week 3
8.200.m (stride/ 1-min interval)
8.100.m (stride/ 30-sec interval)
8.200.m (stride/ 1-min interval)
8.100.m (stride/ 30-sec interval)
Week 4
8.200.m and 8.100.m at 85%
HRmax (stride/ 1-min interval)

Week 5
6.100.m and 5.200.m at 90%
HRmax (30-sec interval)
4.300.m and 3.400.m full
speed runs (1-min interval)
2.500.m full speed runs (1-
min interval)

Week 6
2.100.m and 2.80.m (stride/
30-sec interval)
10.50.m full speed runs (30-
sec interval)
2.100.m and 2.80.m m
(stride/ 30-sec interval)

Week 7
4.100.m and 4.200.m full
speed runs (30-sec interval)
3.300 and 3.400.m (stride/
45-sec interval)
2.500.m (stride/ 1-min
interval)
2.300 and 2.400 full speed
runs (45-sec interval)
3.100 and 3.200.m full speed
runs (30-sec interval)

SE (n = 7)
4 x wk.
E precedes S by 7-hours

C (n = 5)
No training
<table>
<thead>
<tr>
<th>No</th>
<th>Authors</th>
<th>Subjects</th>
<th>Protocol</th>
<th>Tests and Measurements</th>
<th>No Significant Changes</th>
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</table>
| 9  | McCarthy et al. 2002 | 30 sedentary males | S / E / SE | 10 weeks training intervention [3-d-w]:
S
- Eight weight-training exercises (parallel squats, bench presses, standing curls, knee extensions, leg curls, lat pull-downs, overhead presses and heel raises). One warm-up set and three maximal efforts sets. Number of reps to failure ranged between 5 -7. (60-90 sec rest between sets)
E
- 50 min of continuous cycle at 70% heart rate reserve. The first 5 min served as a warm-up.
SE
- Completed both S and E programs in the same training session. The order of S and E was rotated each training day with a 10 -20 min rest period between training modes | Tested pre- and post-training intervention:
S
- Thigh extensor area $(d=0.81)$
- Thigh flexor area $(d=0.41)$
- Type 1 area $(\mu m^2) (d=1.07)$
- Type 2 area $(\mu m^2) (d=1.1)$
- Mean fibre area $(\mu m^2) (d=0.88)$
Dominant side tested:
Computerized tomography.
Muscle biopsy:
Type 1 and type 2.
Strength:
Isometric torque.
EMG.
↑ Thigh extensor area $(d=0.21)$
↑ Thigh flexor area $(d=0)$
↑ Type 2 area $(\mu m^2) (d=0.78)$
↑ Mean fibre area $(\mu m^2) (d=0.66)$
No significant changes in fibre distribution |
| 10 | Gravelle et al. 2000 | 19 active women | S / SE / ES | 11 weeks training intervention:
S $(n=6)$
- 3 x wk. (M, W, F)
- Week 1 - 2
- 2 x 10 RM/ 1-min rest
- Leg press
- Squat
- Knee extension | Tested pre-, mid- and post training intervention.
S
- Body mass pre-mid $(d = 0.01)$
- Body mass pre-post $(d = 0.05)$
Strength:
- Leg press 1 RM
- VO$_{2\text{ max}}$ $(d = 0.28)$
Aerobic and anaerobic capacity:
- Leg press 1 RM
- VO$_{2\text{ max}}$
- Pre-mid $(d = 0.24)$
- Pre-post $(d = 0.26)$
- Mid-post $(d = 0.10)$ | 5/10 No |
<table>
<thead>
<tr>
<th>Exercise</th>
<th>Time Period</th>
<th>Reps/RM</th>
<th>Rest</th>
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<tbody>
<tr>
<td>Knee flexion</td>
<td>Week 3 - 4</td>
<td>3 x 10</td>
<td>1 min</td>
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<td>Heel raise</td>
<td>Week 5 - 5.5</td>
<td>4 x 10</td>
<td>1 min</td>
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<td>Straight leg dead lift</td>
<td>1 week break</td>
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<td>Week 5.5 - 9</td>
<td>4 x10</td>
<td>1 min</td>
</tr>
<tr>
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<td>Weeks 10 - 11</td>
<td>4 x 6 - 8</td>
<td>1 min</td>
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<th>Change in Body Composition</th>
<th>SE (n = 6)</th>
<th>ES (n = 7)</th>
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<tr>
<td>Body mass pre-mid</td>
<td>$d = 0.02$</td>
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<td>Body mass post</td>
<td>$d = 0.07$</td>
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<td>VO$_{2\text{max}}$</td>
<td>$d = 0.28$</td>
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<table>
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<th>Test</th>
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<tr>
<td>Wingate test</td>
<td>Week 3 - 4</td>
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<tr>
<td>Peak anaerobic power (PANP)</td>
<td>Week 3 - 4</td>
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<tr>
<td>Anaerobic capacity (ANC)</td>
<td>Week 3 - 4</td>
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<table>
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<tr>
<th>Change in Test Results</th>
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<td>PANP pre-mid</td>
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<td>PANP post</td>
<td>$d = 0.19$</td>
<td>$d = 0.19$</td>
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<tr>
<td>ANC pre-mid</td>
<td>$d = 0.17$</td>
<td>$d = 0.17$</td>
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<tr>
<td>ANC post</td>
<td>$d = 0.19$</td>
<td>$d = 0.19$</td>
</tr>
<tr>
<td>PANP pre-mid</td>
<td>$d = 0.23$</td>
<td>$d = 0.25$</td>
</tr>
<tr>
<td>PANP post</td>
<td>$d = 0.17$</td>
<td>$d = 0.19$</td>
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<table>
<thead>
<tr>
<th>Change in Leg Press 1 RM</th>
<th>SE (n = 6)</th>
<th>ES (n = 7)</th>
</tr>
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<tbody>
<tr>
<td>Pre-mid</td>
<td>$d = 0.02$</td>
<td>$d = 0.32$</td>
</tr>
<tr>
<td>Post</td>
<td>$d = 0.07$</td>
<td>$d = 0.46$</td>
</tr>
<tr>
<td>Mid-post</td>
<td>$d = 0.04$</td>
<td>$d = 0.20$</td>
</tr>
</tbody>
</table>
Pre-post ($d = 0.22$)
ANC
Pre-mid ($d = 0.18$)
Pre-post ($d = 0.17$)
PANP
Pre-mid ($d = 0.49$)
Pre-post ($d = 0.26$)
ANC
Pre-mid ($d = 0.21$)
Pre-post ($d = 0.20$)

ES
Body mass pre-mid = no change
↑ Body mass pre-post ($d = 0.04$)*
*significantly different from SE
↑ $\text{VO}_2\text{max}$ ($d = 0.19$)
↑ Leg press 1 RM
Pre-mid ($d = 0.38$)
Pre-post ($d = 0.35$)
Mid-post ($d = 0.13$)
% change in Leg press 1 RM
Pre-mid ($d = 0.24$)
Pre-post ($d = 0.27$)
Mid-post ($d = 0.09$)
PANP
Pre-mid ($d = 0.19$)
Pre-post ($d = 0.2$)
ANC
Pre-mid ($d = 0.06$)
Pre-post ($d = 0.01$)
PANP
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Intervention Details</th>
<th>Results</th>
<th>Functional Results</th>
</tr>
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<tbody>
<tr>
<td>Bell et al. 2000</td>
<td>45 men and women (22.3±3.3 years)</td>
<td>S / E / SE / C</td>
<td>12 weeks training intervention: S (n = 7♂, 4♀) 3 x wk. 4% ↑ intensity each week: 72-84% of 1 RM 4 – 12 reps 2 – 6 sets Double leg press Single knee flexion Single knee extension Double leg calf raises Bench press Seated pull-downs Shoulder press Bicep curls E (n = 7♂, 4♀) 3 x wk. 1 x wk. 30 min cycle → 42 min (a 4 min ↑ every 4 weeks) 1 x wk. Intervals: 4 x 3 min cycle at 90% VO₂ max • 3 min rest (↑ x 1 set every 4 weeks until 7 sets completed) SE (n = 8♂, 5♀) 6 x wk</td>
<td>S / E / SE tested pre-/week 6 and post-training intervention. C tested pre- and post-training intervention. Muscle biopsies: Fibre type CSA Enzyme activity Capillary to fibre ratios Blood and urine samples: Serum testosterone Human growth hormone Sex hormone binding globulin Urinary cortisol Physiological tests VO₂ max Strength: Bilateral leg press 1 RM Dominant leg unilateral knee extension 1 RM</td>
</tr>
</tbody>
</table>
days.

C (n = 5♂ 5♀)
No training

<table>
<thead>
<tr>
<th></th>
<th>Pre-mid (d = 0.30)</th>
<th>Pre-post (d = 0.50)</th>
<th>↑ Leg press 1 RM</th>
<th>Pre-mid (d = 0.93)</th>
<th>Pre-post (d = 0.96)</th>
</tr>
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<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>E ♂</td>
<td>↑ VO₂ max</td>
<td>Pre – mid (d = 0.07)</td>
<td>Pre – post (d = 0.13)</td>
<td></td>
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<tr>
<td></td>
<td>↑ Knee extension 1 RM</td>
<td>Pre-mid (d = 0.02)</td>
<td>Pre-post (d = 0.07)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>↑ Leg press 1 RM</td>
<td>Pre-mid (d = 0.45)</td>
<td>Pre-post (d = 0.53)</td>
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</tr>
<tr>
<td>SE ♀</td>
<td>↑ VO₂ max</td>
<td>Pre – mid (d = 0.24)</td>
<td>Pre – post (d = 0.47)</td>
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<tr>
<td></td>
<td>↑ Knee extension 1 RM</td>
<td>Pre-mid (d = 0.39)</td>
<td>Pre-post (d = 0.61)</td>
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<tr>
<td></td>
<td>↑ Leg press 1 RM</td>
<td>Pre-mid (d = 0.76)</td>
<td>Pre-post (d = 1.69)</td>
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<tr>
<td>SE ♂</td>
<td>↑ VO₂ max</td>
<td>Pre – mid (d = 0.13)</td>
<td>Pre – post (d = 0.17)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>↑ Knee extension 1 RM</td>
<td>Pre-mid (d = 0.23)</td>
<td>Pre-post (d = 0.33)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>↑ Leg press 1 RM</td>
<td>Pre-mid (d = 0.32)</td>
<td></td>
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</tr>
<tr>
<td>S</td>
<td>Eight weight-training exercises (parallel squats, bench presses, standing curls, knee extensions, leg curls, lat pull-downs, overhead presses and heel raises). One warm-up set and three maximal effort sets. Number of reps to failure ranged between 5-7. (60-90 sec rest between sets)</td>
<td>S</td>
<td>Dominant leg tested.</td>
<td>S</td>
<td>↑ Isokinetic torque at 0 rad.s(^{-1}) (d = 0.56)</td>
</tr>
<tr>
<td>E</td>
<td>50 min of continuous cycle at 70% heart rate reserve. The first 5 min served as a warm-up.</td>
<td>E</td>
<td>Strength:</td>
<td>E</td>
<td>↑ Isokinetic torque at 3.35 rad.s(^{-1}) (d = 0.41)</td>
</tr>
<tr>
<td>SE</td>
<td>Completed both S and E programs in the same training session. The order of S and E</td>
<td>SE</td>
<td>Isometric, 3 maximal knee extension torque at a specific angle for four velocities (0, 1.68, 3.35 and 5.03 rad.s(^{-1}))</td>
<td>SE</td>
<td>Peak respiratory exchange ratio (d = 1.33)</td>
</tr>
</tbody>
</table>

Pre-post (d = 0.67)

C ♀

↓ VO\(_2\)\(_{\text{max}}\) (d = 0.13)

↑ Knee extension 1 RM (d = 0.2)

↑ Leg press 1 RM (d = 0.12)

C ♂

↓ VO\(_2\)\(_{\text{max}}\) (d = 0.12)

↑ Knee extension 1 RM (d = 0.07)

↑ Leg press 1 RM (d = 0.13)

S / E / SE (27.9±1.2 years)

E (26.5±1.6 years)

SE (27.3±1.7 years)

18 weight-training exercises (parallel squats, bench presses, standing curls, knee extensions, leg curls, lat pull-downs, overhead presses and heel raises). One warm-up set and three maximal effort sets. Number of reps to failure ranged between 5-7. (60-90 sec rest between sets)
was rotated each training day with a 10-20 min rest period between training modes

| 13 | Kraemer et al. 1995 | 35 US Army men | S / E / SE / C | Training intervention 4 x wk (M, T, T, F) over 12 weeks. | S (n = 9) (24.3±5.1 years) Afternoon (Mon & Thurs) 3 x 10 RM Bench press Fly 2 x 10 RM Military press Upright row 3 x 10 RM Lat pull-down Seated row Arm curl 2 x 25 RM Sit-up 3 x 10 RM Single knee extension Single le curl 3 x 15 RM Calf raise 3 x 10 RM Split squat (Tue & Thur) 5 x 5 RM Bench press Military press Arm curl | Tested pre-4wk-8wk and 12wk (post) intervention Strength: Bench press 1 RM Leg press 1 RM Military press 1 RM Double leg extension 1 RM Aerobic capacity: VO2 max Wingate test Muscle biopsy: Fibre type CSA Blood samples: Serum Testosterone Serum cortisol | S [Pre – 4wk] [Pre – 4wk] [Pre – 4wk] [Pre – 4wk] [Pre – 4wk] [Pre – Post] [Pre – Post] [Pre – Post] | 5/10 | Yes |

SE

↑ Isokinetic torque at 0 rad.s^{-1} (d = 0.08)
↑ % fat (d = 0.28)
↑ 1RM Squat (d = 0.82)
↑ 1RM Bench Press (d = 0.5)
↑ Vertical Jump (d = 0.57)
↑ VO2peak (ml.kg^{-1}min^{-1}) (d = 0.88)
↑ VO2peak (ml.kg^{-1} FFM^{-1} min^{-1}) (d = 1.01)
<table>
<thead>
<tr>
<th>Exercise</th>
<th>Reps/Reps/ Sets</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat pull-down</td>
<td></td>
<td></td>
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<tr>
<td>Obliques</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sit-up</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 x 10 RM</td>
<td></td>
<td></td>
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<tr>
<td>Calf raise</td>
<td></td>
<td></td>
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<tr>
<td>5 x 5 RM</td>
<td></td>
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<tr>
<td>Double knee extension</td>
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<tr>
<td>Leg press</td>
<td></td>
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<tr>
<td>4 x 6 RM</td>
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<tr>
<td>Dead lift</td>
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<tr>
<td>2 – 3-min rest between sets.</td>
<td></td>
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<tr>
<td>E (n = 8) (21.4±34.1 years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Mon &amp; Thur)</td>
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<tr>
<td>Warm-up</td>
<td></td>
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</tr>
<tr>
<td>Max dist in 40-min at 80 – 85% VO_{2 max} (Tue &amp; Fri)</td>
<td>200 – 800.m intervals at 95 – 100% VO_{2 max}</td>
<td>Exercise-to-rest = 1:4 – 1:0.5</td>
</tr>
<tr>
<td>ES (n = 9) (23.3±3.6 years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E morning 5 – 6 hours before</td>
<td></td>
<td></td>
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<tr>
<td>S afternoon</td>
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</tr>
<tr>
<td>Upper-SE (n = 9) (24.3±5.0 years)</td>
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<td></td>
</tr>
<tr>
<td>E morning 5 – 6 hours before</td>
<td></td>
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<tr>
<td>S afternoon</td>
<td></td>
<td></td>
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<tr>
<td>(Mon &amp; Thurs)</td>
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<tr>
<td>3 x 10 RM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bench press</td>
<td></td>
<td></td>
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<tr>
<td>Fly</td>
<td></td>
<td></td>
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<tr>
<td>2 x 10 RM</td>
<td></td>
<td></td>
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<tr>
<td>Military press</td>
<td></td>
<td></td>
</tr>
<tr>
<td>† Wingate (Peak power) legs ($d = 1.02$)</td>
<td>† Wingate (Mean power) legs ($d = 1.11$)</td>
<td>† Wingate (Peak power) arms ($d = 0.56$)</td>
</tr>
<tr>
<td>↓ VO_{2 max} ($d = 0.10$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Pre – 4wk]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>† Double leg extension 1 RM ($d = 0.04$)</td>
<td>† Double leg extension 1 RM ($d = 0.00$)</td>
<td>† Double leg extension 1 RM ($d = 0.01$)</td>
</tr>
<tr>
<td>[Pre – 8wk]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ Leg press 1 RM ($d = 0.01$)</td>
<td></td>
<td></td>
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<tr>
<td>[Pre – 8wk]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ Leg press 1 RM ($d = 0.02$)</td>
<td></td>
<td></td>
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<tr>
<td>[Pre – Post]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ Leg press 1 RM ($d = 0.01$)</td>
<td></td>
<td></td>
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<tr>
<td>[Pre – 8wk]</td>
<td></td>
<td></td>
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<tr>
<td>↓ Bench press 1 RM ($d = 0.01$)</td>
<td></td>
<td></td>
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<tr>
<td>[Pre – 8wk]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ Bench press 1 RM ($d = 0.02$)</td>
<td></td>
<td></td>
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<tr>
<td>[Pre – Post]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ Bench press 1 RM ($d = 0.01$)</td>
<td></td>
<td></td>
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<tr>
<td>[Pre – 8wk]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ Military press 1 RM ($d = 0.01$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Pre – 8wk]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ Military press 1 RM ($d = 0.02$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Pre – Post]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ Military press 1 RM ($d = 0.02$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Pre – Post]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ Wingate (Peak power) legs ($d = 0.10$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Upright row 3 x 10 RM
Lat pull-down
Seated row
Arm curl 2 x 25 RM
Sit-up 3 x 10 RM
(Tue & Thur)
5 x 5 RM
Bench press
Military press
Arm curl
Lat pull-down
Obliques
Sit-up

C (n = 5) (22.4±4.2 years)

↓ Wingate (Mean power) legs ($d = 0.23$)
↓ Wingate (Peak power) arms ($d = 0.05$)
↑ Wingate (Mean power) arms ($d = 0.25$)
↑ VO$_{2\text{max}}$ ($d = 0.99$)
SE

↑ Double leg extension 1 RM ($d = 0.06$)
[Pre – 4wk]
↑ Double leg extension 1 RM ($d = 0.06$)
[Pre – Post]
↑ Double leg extension 1 RM ($d = 0.14$)

↑ Leg press 1 RM ($d = 0.07$)
[Pre – 4wk]
↑ Leg press 1 RM ($d = 0.09$)
[Pre – 8wk]
↑ Leg press 1 RM ($d = 0.15$)
[Pre – Post]

↑ Bench press 1 RM ($d = 0.08$)
[Pre – 4wk]
↑ Bench press 1 RM ($d = 0.12$)
[Pre – 8wk]
↑ Bench press 1 RM ($d = 0.17$)
[Pre – Post]

↑ Military press 1 RM ($d = 0.04$)
[Pre – 4wk]
↑ Military press 1 RM ($d = 0.15$)
[Pre – 8wk]
↑ Military press 1 RM ($d = 0.35$)
[Pre – Post]
↑ Wingate (Peak power) legs ($d = 0.45$)
↑ Wingate (Mean power) legs ($d = 0.39$)
↑ Wingate (Peak power) arms ($d = 0.58$)
↑ Wingate (Mean power) arms ($d = 1.03$)
[Pre- Post]
↑ $\text{VO}_2\text{max}$ ($d = 0.64$)

Upper-SE
[Pre – 4wk]
↑ Double leg extension 1 RM ($d = 0.03$)
[Pre – 8wk]
↑ Double leg extension 1 RM ($d = 0.05$)
[Pre – Post]
↑ Double leg extension 1 RM ($d = 0.03$)

[Pre – 4wk]
↑ Leg press 1 RM ($d = 0.03$)
[Pre – 8wk]
↑ Leg press 1 RM ($d = 0.03$)
[Pre – Post]
↑ Leg press 1 RM ($d = 0.06$)

[Pre – 4wk]
↑ Bench press 1 RM ($d = 0.07$)
[Pre – 8wk]
↑ Bench press 1 RM ($d = 0.09$)
[Pre – Post]
↑ Bench press 1 RM ($d = 0.15$)

[Pre – 4wk]
↑ Military press 1 RM ($d = 0.02$)
[Pre – 8wk]
↑ Military press 1 RM ($d = 0.13$)
[Pre – Post]
↑ Military press 1 RM ($d = 0.22$)

[Pre – Post]
↑ Wingate (Peak power) legs ($d = 0.36$)
↑ Wingate (Mean power) legs ($d = 0.17$)
↑ Wingate (Peak power) arms ($d = 0.46$)
↑ Wingate (Mean power) arms ($d = 0.55$)

[Pre- Post]
↑ $\text{VO}_2\text{max}$ ($d = 0.84$)
Hennessy et al. 1994

56 rugby-trained men (9 withdrew)

8 weeks training intervention.

S (n = 9)
- 3-d per wk
- 1x wk
- 3 x 10 RM
- Lunge
- Upright row
- Dumbbell flies
- Triceps press
- Calf raise
- Bent knee sit-ups

2 x wk
- Week 1
  - 2 x 10 reps at 65% of 1 RM
  - Back squats
  - Bench press
  - Hamstring curls
  - Lat pull down
  - Shoulder press
  - Arm curls
  - 2 x 15 reps at 65% 1RM
  - Abdominal crunches

Week 2
- 3 x 8 reps at 70% of 1 RM
- Back squats
- Bench press
- 3 x 10 reps at 70% of 1 RM
- Hamstring curls
- Lat pull down
- Shoulder press
- Arm curls
- 3 x 15 reps at 70% of 1 RM
- Abdominal crunches

Week 3
- 4 x 8 reps at 75% of 1 RM
- Back squat

S
- Test pre- and post-training intervention.
  - S
  - 3-d per wk
  - 1x wk
  - 3 x 10 RM
  - Lunge
  - Upright row
  - Dumbbell flies
  - Triceps press
  - Calf raise
  - Bent knee sit-ups

2 x wk
- Week 1
  - 2 x 10 reps at 65% of 1 RM
  - Back squats
  - Bench press
  - Hamstring curls
  - Lat pull down
  - Shoulder press
  - Arm curls
  - 2 x 15 reps at 65% 1RM
  - Abdominal crunches

Week 2
- 3 x 8 reps at 70% of 1 RM
- Back squats
- Bench press
- 3 x 10 reps at 70% of 1 RM
- Hamstring curls
- Lat pull down
- Shoulder press
- Arm curls
- 3 x 15 reps at 70% of 1 RM
- Abdominal crunches

Week 3
- 4 x 8 reps at 75% of 1 RM
- Back squat

S
- Bench press (d = 1.30)
- Squat (d = 1.26)
- Vertical jump (d = 0.67)
- Vertical jump
- 200.m sprint speed (d = 0.47)
- EVO$_{2max}$ (d = 0.05)
- Bench press 1 RM
- Squat 1 RM
- Vertical jump (d = 0.61)
- 200.m sprint speed (d = 0.09)
- EVO$_{2max}$ (d = 1.72)
- Bench press (d = 0.04)
- Squat (d = 0.19)

E
- Vertical jump (d = 0.04)
- 200.m sprint speed (d = 0.09)
- EVO$_{2max}$ (d = 1.13)

SE
- Bench press (d = 1.22)
- Squat (d = 0.57)
- Vertical jump (d = 0.04)
- 200.m sprint speed (d = 0.09)
- EVO$_{2max}$ (d = 1.13)

C
- Bench press (d = 0.09)
- Squat (d = 0.04)
- Vertical jump (d = 0.17)
- 200.m sprint speed (d = 0.13)
Bench press
3 x 10 reps at 75% 1 RM
Hamstring curls
Lat pull down
Shoulder press
Arm curls
3 x 20 reps at 75% of 1 RM
Abdominal crunches

Week 4
5 x 6 reps at 80% of 1 RM
Back squat
Bench press
3 x 10 reps at 80% of 1 RM
Hamstring curls
Lat pull down
Shoulder press
Arm curls
3 x 25 reps at 80% of 1 RM
Abdominal crunches

Week 5
5 x 6 reps at 85% of 1 RM
Back squat
Bench press
3 x 10 reps at 85% of 1 RM
Hamstring curls
Lat pull down
Shoulder press
Arm curls
3 x 25 at 85% of 1 RM
Abdominal crunches

Week 6
5 x max at 90% of 1 RM
Back squat
Bench press
3 x 10 reps at 90% of 1 RM
Hamstring curls
Lat pull down

↓ EVO_{2max} (d = 0.53)
Shoulder press
Arm curls
3 x 25 at 90% of 1 RM
Abdominal crunches

Week 7
5 x max at 95% of 1 RM
Back squat
Bench press
3 x 10 reps at 95% of 1 RM
Hamstring curls
Lat pull down
Shoulder press
Arm curls
3 x 25 at 95% of 1 RM
Abdominal crunches

Week 8
6 x max reps at 105% of 1 RM
Back squat
Bench press
3 x 10 reps at 105% of 1 RM
Hamstring curls
Lat pull down
Shoulder press
Arm curls
3 x 25 at 105% of 1 RM
Abdominal crunches

E (n = 12)
4-d per wk
2 x wk
Low intensity run at 70%
HRmax gradually increasing
from 20-min week 1 to 60-min week 8.
1 x wk
Fartlek run
5-min jog \(\rightarrow\) fast striding
200.m \(\rightarrow\) 200.m jog. Several times. \(\rightarrow\)
Fast strides (30 -100.m) \(\rightarrow\)
recovery jog. Several times. \(\rightarrow\) 5-min jog. Session duration gradually increased from 15-min at week 1 to 35-min at week 8.

1 x wk
Run at 85% HRmax, duration gradually increasing from 20-min at week 1 to 40-min at week 5 and then maintained to week 8.

SE (n = 10)
5-d per wk
Mon.
Run 70% HRmax
Moderate intensity weights
Tue.
Fartlek
Wed.
High intensity weights
Run 70% HRmax
Thu.
Rest
Fri.
Run 85 % HRmax
Sat.
High intensity weights

C (n = 10)
No training
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Intervention Details</th>
<th>Tested Pre-Post</th>
<th>Body Composition</th>
<th>Thigh Girth</th>
<th>Strength</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volpe et al. 1993</td>
<td>25 sedentary women (18-30 years)</td>
<td>9 weeks training intervention</td>
<td>S (n = 8)</td>
<td>S</td>
<td>SE</td>
<td>C</td>
<td>6/10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3-d per week</td>
<td>Leg press</td>
<td>Leg extension</td>
<td>Legs</td>
<td>Abdominals</td>
</tr>
</tbody>
</table>
Week 3 – 8
Mon & Fri
4 x 4 - 6 reps 75% of 1 RM
Leg press
Leg extension
Leg curls
Calf raises
3 x 4 - 6 reps 75% of 1 RM
Arm curls
Bench press
Triceps press
Shoulder shrugs
Lat pull downs
Military press
Chest flies
Chest press
Abdominals

Wed
3 x 4 – 6 reps 75% of 1 RM
Leg press
Leg extension
Leg curls
Calf raises
4 x 4 – 6 reps 75% of 1RM
Arm curls
Bench press
Triceps press
Shoulder shrugs
Lat pull downs
Military press
Chest flies
Chest press
Abdominals

SE (n = 10)
Number of training days ad S
group
25-min run at 75% HRmax
30-min of legs and 4 arm apparatus of their choice reps and sets as S group.

C (n = 7)
No training

<table>
<thead>
<tr>
<th>16</th>
<th>Bell et al.</th>
<th>31 subjects with previous experience of both or either strength endurance training</th>
<th>12 weeks training intervention. S (n = 15) (T, T, S) 2 sets at each station, 8 – 15 reps at ~ 1.05 rad.s(^{-1}) Unilateral seated knee extension/ flexion Bilateral hip and knee extension 8 other upper and lower body stations (not detailed in this article) Bent knee sit-ups (Progressed by adding an extra 1/3 of the circuit every 3 weeks) [1x wk Moderate intensity 30-min E session for aerobic maintenance]</th>
<th>Tested 4 weeks, 6 and 3 days prior to training intervention and 3, 6, 9 weeks during the intervention and at 12 weeks upon completion. Aerobic capacity: (VO_2\text{max}) Blood samples: Lactate levels Strength: Knee extension peak torque. Total work during max knee extension x 4 CT scan: CSA of Quadriceps</th>
<th>5/10</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>S / SE</td>
<td>[4 weeks – 6 weeks]</td>
<td>Knee extension peak torque ((d = 0.02))</td>
<td>[4 weeks – 9 weeks]</td>
<td>Knee extension peak torque ((d = 0.15))</td>
<td>[4 weeks – 12 weeks]</td>
</tr>
<tr>
<td>SE</td>
<td></td>
<td>[4 weeks – 6 weeks]</td>
<td>Knee extension total work ((d = 0.04))</td>
<td>[4 weeks – 9 weeks]</td>
<td>Knee extension total work ((d = 0.10))</td>
<td>[4 weeks – 12 weeks]</td>
</tr>
<tr>
<td>S</td>
<td>S((22±1.9) years)</td>
<td>↑ Knee extension peak torque ((d = 0.02))</td>
<td>[4 weeks – 6 weeks]</td>
<td>↑ Knee extension peak torque ((d = 0.15))</td>
<td>[4 weeks – 12 weeks]</td>
<td>↑ Knee extension peak torque ((d = 0.08))</td>
</tr>
<tr>
<td>SE</td>
<td>SE((25±3.6) years)</td>
<td>↑ Knee extension total work ((d = 0.04))</td>
<td>[4 weeks – 9 weeks]</td>
<td>↑ Knee extension total work ((d = 0.10))</td>
<td>[4 weeks – 12 weeks]</td>
<td>↑ Knee extension total work ((d = 0.15))</td>
</tr>
<tr>
<td>S</td>
<td>[4 weeks – 6 weeks]</td>
<td>Knee extension peak torque ((d = 0.02))</td>
<td>[4 weeks – 9 weeks]</td>
<td>Knee extension peak torque ((d = 0.15))</td>
<td>[4 weeks – 12 weeks]</td>
<td>Knee extension peak torque ((d = 0.08))</td>
</tr>
<tr>
<td>SE</td>
<td>SE</td>
<td>Knee extension total work ((d = 0.19))</td>
<td>[4 weeks – 9 weeks]</td>
<td>Knee extension total work ((d = 0.24))</td>
<td>[4 weeks – 12 weeks]</td>
<td>Knee extension total work ((d = 0.31))</td>
</tr>
</tbody>
</table>
Nelson et al. (1990) investigated the effects of 20 weeks of training on untrained men. Untrained men, S (27.0 ± 1.1 years) and E (30.0 ± 2.4 years), were trained on separate days. S training always preceded E by 10 m.

**Training Intervention**

- **E** (n = 4) performed a constant pedal rate of 83 rpm on a Monarch ergometer at: Week 1: 30 min at 75% MHR, Weeks 2–5: 60–50–60 m at 85% MHR, Week 7: 60 m at 85% MHR.
- **S** (n = 5) performed 3 × 6RM using a dynamometer (30°/sec) with a 90-s rest between sets: Week 8– onwards: 60–50–60 m respectively.

**Testing**

- **Day 1:** Strength: Torque production; R knee extension 30°, 60° and 180°/sec, Aerobic capacity: VO\textsubscript{2} max
- **Day 2:** Strength: Torque production; R knee extension 30°, 60° and 180°/sec, Aerobic capacity: VO\textsubscript{2} max
- **Day 3:** Muscle biopsies (VL) 60%–90% MHR, 30 m at 75% MHR, 20 m at 80% MHR, 10 m at 85% MHR.

**Results**

- **E:**
  - Torque 30°/sec (d = 0.49)
  - Torque 60°/sec (d = 0.9)
  - Torque 180°/sec (d = 0.69)
  - VO\textsubscript{2} max;
  - 0–11 weeks (d = 0.42)
  - 0–20 weeks (d = 0.88)
  - 11–20 weeks (d = 0.03)
- **S:**
  - Torque 30°/sec (d = 0.04)
  - Torque 60°/sec (d = 0.88)
  - Torque 180°/sec (d = 0.74)
  - VO\textsubscript{2} max;
  - 0–11 weeks (d = 0.04)
  - 0–20 weeks (d = 0.76)
  - 11–20 weeks (d = 0.03)

- **Muscle Biopsies**
  - **Citrate synthase:**
    - 0–11 weeks (d = 1.59)
    - 0–20 weeks (d = 1.17)
    - 11–20 weeks (d = 0.04)
  - **Muscle fibre area, type 1:**
    - 0–11 weeks (d = 0.33)
    - 0–20 weeks (d = 0.33)
    - 11–20 weeks (d = 0.29)
  - **Muscle fibre area, type 2a:**
    - 0–11 weeks (d = 0.12)
    - 0–20 weeks (d = 0.03)
    - 11–20 weeks (d = 0.76)

**Significance**

- Yes
↑ Torque 30°/sec ($d = 1.74$)
↑ Torque 60°/sec ($d = 1.36$)
↑ Torque 180°/sec ($d = 1.06$)

↑ $\text{VO}_2\max$;
0–11 weeks ($d = 0.05$)
0–20 weeks ($d = 0.05$)
11–20 weeks ($d = 0.11$)

↑ Muscle fibre area, type 1;
0–11 weeks ($d = 0.10$)
↓ Muscle fibre area, type 1;
0–20 weeks ($d = 0.10$)

↑ Muscle fibre area, type 2b;
0–11 weeks ($d = 0.14$)
0–20 weeks ($d = 0.5$)

↑ Muscle fibre area, type 2b;
0–11 weeks ($d = 0.59$)
0–20 weeks ($d = 0.86$)

↑ VO$_2$ max;
0–11 weeks ($d = 0.58$)
0–20 weeks ($d = 1.08$)
11–20 weeks ($d = 0.38$)

↑ Fibre type 1 (%);
0–20 weeks ($d = 0.75$)
↑ Fibre type 2a (%);
0–11 weeks ($d = 10.46$)
<table>
<thead>
<tr>
<th>18</th>
<th>Sale et al. 1989</th>
<th>16 men, 1 withdrew (no previous training experience)</th>
<th>SE non-concurrent / SE concurrent</th>
<th>20 weeks training intervention (including 3 week break at mid-point)</th>
<th>Tested pre-before break and post-training intervention.</th>
<th>N-SE</th>
<th>N-SE (n =8)</th>
<th>VO\textsubscript{2} max</th>
<th>C-SE</th>
<th>C-SE (21.6±0.5 years)</th>
<th>VO\textsubscript{2} max (d = 0.21)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-SE (21.3±0.8 years)</td>
<td>4 x wk: 2 days S, 2 days E S</td>
<td>N-SE (n =8)</td>
<td>Aerobic capacity: VO\textsubscript{2} max</td>
<td>C-SE</td>
<td>C-SE (21.6±0.5 years)</td>
<td>VO\textsubscript{2} max (d = 0.21)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-SE</td>
<td>Week 1 – Week 4</td>
<td>Week 1 – Week 4</td>
<td>Week 1 – Week 4</td>
<td>Week 1 – Week 4</td>
<td>Week 5 – Week 7</td>
<td>Week 5 – Week 7</td>
<td>Week 5 – Week 7</td>
<td>Week 5 – Week 7</td>
<td>Week 8</td>
<td>Week 8</td>
<td></td>
</tr>
<tr>
<td>3 x 15 – 20 reps at 50, 70, 90% of 1 RM</td>
<td>3 x 15 – 20 reps at 50, 70, 90% of 1 RM</td>
<td>3 x 15 – 20 reps at 50, 70, 90% of 1 RM</td>
<td>3 x 15 – 20 reps at 50, 70, 90% of 1 RM</td>
<td>3 x 15 – 20 reps at 50, 70, 90% of 1 RM</td>
<td>7 sets</td>
<td>7 sets</td>
<td>7 sets</td>
<td>7 sets</td>
<td>6 sets</td>
<td>6 sets</td>
<td></td>
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<tr>
<td>Leg press</td>
<td>Leg press</td>
<td>Leg press</td>
<td>Leg press</td>
<td>Leg press</td>
<td>Week 9– 12 break from intervention</td>
<td>Week 9– 12 break from intervention</td>
<td>Week 9– 12 break from intervention</td>
<td>Week 9– 12 break from intervention</td>
<td>Week 13 – 14</td>
<td>Week 13 – 14</td>
<td></td>
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<tr>
<td>6 sets</td>
<td>6 sets</td>
<td>6 sets</td>
<td>6 sets</td>
<td>6 sets</td>
<td>Week 15 – 17</td>
<td>Week 15 – 17</td>
<td>Week 15 – 17</td>
<td>Week 15 – 17</td>
<td>Week 15 – 17</td>
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<td>7 sets</td>
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<td>7 sets</td>
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</tr>
</tbody>
</table>

↑ Muscle fibre area, type 1; 0 – 11 weeks (d = 0.43) 0 – 20 weeks (d = 0.59) 11 – 20 weeks (d = 0.18)  
↑ Muscle fibre area, type 2a; 0 – 11 weeks (d = 0.67) 0 – 20 weeks (d = 2.0) 11 – 20 weeks (d = 0.92)  
↑ Muscle fibre area, type 2b; 0 – 11 weeks (d = 0.30) 0 – 20 weeks (d = 0.88) 11 – 20 weeks (d = 0.66)
<table>
<thead>
<tr>
<th>Week 18 – End</th>
<th>8 sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td></td>
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<tr>
<td>Week 1 – Week 4</td>
<td></td>
</tr>
<tr>
<td>2 x 3-min bouts/ 3-min rest at 60 and 80% VO$_{2\text{max}}$ cycle ergometer</td>
<td></td>
</tr>
<tr>
<td>4 x 3-min bouts/ 3-min rest at 90 – 100% VO$_{2\text{max}}$ cycle ergometer</td>
<td></td>
</tr>
<tr>
<td>Week 5 – Week 7</td>
<td></td>
</tr>
<tr>
<td>7 bouts</td>
<td></td>
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<tr>
<td>Week 8</td>
<td></td>
</tr>
<tr>
<td>8 bouts</td>
<td></td>
</tr>
</tbody>
</table>

*Weeks 9-12 break from intervention*

<table>
<thead>
<tr>
<th>Week 13 – 14</th>
<th>6 bouts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 15 – 17</td>
<td>7 bouts</td>
</tr>
<tr>
<td>Week 18 – End</td>
<td>8 bouts</td>
</tr>
<tr>
<td>C-SE (n = 7)</td>
<td></td>
</tr>
<tr>
<td>2 x wk SE [1st session E preceded S, 2nd session S preceded E]</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>19</th>
<th>Hunter et al. 1987</th>
<th>35 subjects (9 subjects in TES were previously trained)</th>
<th>12 weeks training intervention.</th>
<th>Tested pre- and post-training intervention.</th>
<th>5/10</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S / ES / TES / E</td>
<td>S (n = 5♂ 5♀) 4-d per week 3 x 7 – 10 RM Bench press Seated press</td>
<td></td>
<td>S ♦ Bench press 1 RM (d = 0.19) Squat 1 RM (d = 0.34)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strength: Bench press 1 RM Squat 1 RM</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>♦ Vertical jump (d = 0.16)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>♦ VO$_{2\text{max}}$ (d = 0.01)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
endurance athletes. S and E groups were previously untrained (Age range not documented)  

<table>
<thead>
<tr>
<th>Lat pull down</th>
<th>Two hand curl</th>
<th>Squat</th>
<th>Leg curl</th>
<th>Cleans</th>
<th>Bent leg sit ups</th>
<th>2-d per week E and S same day</th>
<th>2-d per week S only</th>
<th>2-d per week E only</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES (n = 5♂ 3♀)</td>
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<td></td>
</tr>
<tr>
<td>TES (n = 4♂ 5♀)</td>
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</tr>
</tbody>
</table>

Acted as control  

4-d per week  

20-min continuous run at 75% HRmax  

Progressed to 40-min at week 8  

| Vertical jump | Aerobic capacity: $VO_{2\text{max}}$ | Anthropometry: 
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ES</td>
<td>$\uparrow$ Bench press 1 RM ($d = 0.16$)</td>
<td>$\uparrow$ Squat 1 RM ($d = 0.22$)</td>
</tr>
<tr>
<td></td>
<td>$\uparrow$ Vertical jump ($d = 0.09$)</td>
<td>$\uparrow$ $VO_{2\text{max}}$ ($d = 0.15$)</td>
</tr>
<tr>
<td>TES</td>
<td>$\uparrow$ Bench press 1 RM ($d = 0.18$)</td>
<td>$\uparrow$ Squat 1 RM ($d = 0.33$)</td>
</tr>
<tr>
<td></td>
<td>$\uparrow$ Vertical jump ($d = 0.23$)</td>
<td>$\uparrow$ $VO_{2\text{max}}$ ($d = 0.03$)</td>
</tr>
<tr>
<td>E</td>
<td>$\uparrow$ Bench press 1 RM ($d = 0.04$)</td>
<td>$\uparrow$ Squat 1 RM ($d = 0.08$)</td>
</tr>
<tr>
<td></td>
<td>$\uparrow$ Vertical jump ($d = 0.03$)</td>
<td>$\uparrow$ $VO_{2\text{max}}$ ($d = 0.09$)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>20</th>
<th>Dudley et al. 1985</th>
<th>S / E / SE</th>
<th>7 weeks training intervention.</th>
<th>Tested pre- and 14-day intervals and post-training intervention.</th>
<th>Improvements in average maximal torque for S and ES were given in percentages and the figures did not specify either $SD$ or $SE$, therefore $d$ values could not be calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>subjects</td>
<td>22 (8♂ 14♀)</td>
<td>S (n = 6) 3 x wk (alternate days) 2 x isokinetic knee extension 4.19 rad.s$^{-1}$ max efforts for 30-sec (26 – 28 reps) 5-min rest between sets Right and left legs trained</td>
<td>Aerobic capacity: $VO_{2\text{max}}$</td>
<td>E $\uparrow$ Absolute $VO_{2\text{max}}$ ($d = 0.10$)</td>
</tr>
<tr>
<td></td>
<td>not trained</td>
<td></td>
<td>E (n = 10) 3 x wk (alternate days) 5 x 5-min – 5-min recovery interval cycle (mean power $W = 168.9 \pm 10.5$ SE). Progressed by ~ 8W each</td>
<td>Strength: Max peak torque knee extension, angle specific for 7 velocities.</td>
<td>SE $\uparrow$ Absolute $VO_{2\text{max}}$ ($d = 0.81$)</td>
</tr>
<tr>
<td></td>
<td>for 3 months</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>prior to study</td>
<td></td>
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<tr>
<td></td>
<td>E (20.6±0.5 years)</td>
<td></td>
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<tr>
<td></td>
<td>S (25.7±2.4 years)</td>
<td></td>
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</tr>
</tbody>
</table>
ES (22.2±1.8 years)

SE (n = 6)
6 x wk (alternating E and S)
5 x 5-min – 5-min recovery interval cycle (mean power W = 159.8 ± 8.9 SE)
Progressed by ~ 8W each week.

Hickson et al. 1980

21 subjects not trained for 3 months prior to study.

23 subjects

10 weeks training intervention.

S (n = 7♂ 1♀)
5-d per week
5 x 5 reps at 80% of 1 RM
Parallel squats
3 x 5 reps at 80% of 1 RM
Knee flexion
Knee extension
Alternate days:
3 x 5 reps at 80% of 1 RM
Leg press
3 x 20 reps at 80% of 1 RM
Calf raises

ES (18 – 37 years mean = 26)

E (n = 5♂ 3♀)
3-d per week
6 x 5-min cycle ergometer near to VO₂ max/ 2-min rest
Alternate days:
Week 1
30-min continuous run as fast as possible.
Week 2
35-min continuous run as fast as possible.

Tested at pre-, mid- and post-training intervention. Strength was tested on a weekly basis.

Changes in strength improved for S and ES up to week 7, then ES plateaued and started to decline.

ES

S

[Pre – Week 7]
↓ Strength (d = 0.73)

[Pre – Week 8]
↓ Strength (d = 0.81)

[Pre – Week 9]
↓ Strength (d = 0.38)

[Pre – Week 10]
↓ Strength (d = 0.40)

[Pre – Week 10]
↑ Absolute VO₂ max (d = 0.06)

E

[Pre – Week 5]
↑ Absolute VO₂ max (d = 0.15)

[Pre – Week 10]
↑ Absolute VO₂ max (d = 0.27)

ES

[Pre – Week 7]
↑ Strength (d = 0.34)

[Pre – Week 8]
↔ Strength (d = 0.69)

[Pre – Week 9]

5/10 Yes
Week 3 - End
40-min continuous run as fast as possible.

ES (n = 5♂ 2♀)
Combined E and S performed on same days to the same intensity as above ~ 2-hr rest between. Sequencing of S prior to E or E prior to S was not documented in the article.

| Exc | Cadore et al. 2012 | 26 males (64.7±4.1 years) | SE / ES | 12 weeks training intervention 3 x wk, non-consecutive days: Each session was preceded with flexibility and 25 reps of a very light load for upper and lower body exercises. [Control (n = 8) tested prior to study at weeks -4 and 0.] SE (n = 18) Bench Press, inclined leg press, seated row, knee extension, inverse fly, leg curl, triceps curl, biceps curl and abdominal exercises. Week 1 – 2 2 sets of 18 – 20RM Weeks 3 - 4 15 – 17 RM Weeks 5 - 7 | Tested pre- and post-intervention. (-4 weeks – 0 = control period) Muscle Strength: 1 RM bilateral elbow and knee extensors. Isometric peak torque knee flexion and extension at 120°. EMG: VL, RF, BF Muscle thickness: 7.5-MHz US scan of VL, VM, VI, RF (lower limb) and BB, BR (upper limb) Aerobic capacity: VO2peak HR VT1 VT2 | SE | 5/10 | N/A |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↓ Strength (d = 0.13) [Pre – Week 10] ↓ Strength (d = 0.16) [Pre – Week 5] ↑ Absolute VO2max (d = 0.16) [Pre – Week 10] ↑ Absolute VO2max (d = 0.23) | ↑ Upper body 1 RM (d = 1.14) ↑ Lower body 1 RM (d = 2.06) ↑ Knee extensors peak torque (d = 0.71) ↑ Knee flexors peak torque (d = 0.55) ↑ Knee extensors RFD (d = 0.36) ↑ Knee extensors max RFD (d = 0.27) ↑ VL muscle thickness (d = 0.51) ↑ VM muscle thickness (d = 0.93) ↑ VI muscle thickness (d = 0.38) ↑ RF muscle thickness (d = 0.13) ↑ QF muscle thickness (d = 0.75) ↑ BB muscle thickness (d = 0.30) ↑ BR muscle thickness (d = 0.62) ↑ EF muscle thickness (d = 0.86) ↑ Neuromuscular activity VL (d = 0.17) ↑ Neuromuscular activity RF (d = 0.56) ↓ Antagonist co-activation (d = 0.15) ↓ Neuromuscular economy VL (d = 0.95) ↓ Neuromuscular economy RF (d = 0.91) ↓ Upper body 1 RM (d = 0.67)
<table>
<thead>
<tr>
<th>Exercise (Exc)</th>
<th>Cadore et al. 2011</th>
<th>Participants</th>
<th>Type (S/E/SE)</th>
<th>Duration</th>
<th>Intervention Details</th>
<th>Data Collection</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE</td>
<td>29 men (65 ± 5 years)</td>
<td>S/E/SE</td>
<td>12 weeks training intervention</td>
<td>3 x wk, non-consecutive days:</td>
<td>Tested twice before training at 4 weeks prior and at the start of the training intervention and at week 12.</td>
<td>S</td>
<td>No significant changes from pre-training.</td>
</tr>
<tr>
<td></td>
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<td>6 x 4-min bouts at 100% of HR&lt;sub&gt;VT&lt;/sub&gt; with 1-min recovery between bouts.</td>
<td>E</td>
<td>↓ EMG RF 50W (&lt;i&gt;d&lt;/i&gt; = 1.00)</td>
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<td></td>
<td>E</td>
<td>↓ EMG RF 75W (&lt;i&gt;d&lt;/i&gt; = 0.64)</td>
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<td>E</td>
<td>↓ EMG RF 100W (&lt;i&gt;d&lt;/i&gt; = 0.50)</td>
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<td>E</td>
<td>↑ &lt;i&gt;W&lt;/i&gt;&lt;sub&gt;max&lt;/sub&gt; (&lt;i&gt;d&lt;/i&gt; = 0.67)</td>
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<td></td>
<td></td>
<td>E</td>
<td>↑ &lt;i&gt;VO&lt;/i&gt;&lt;sub&gt;2peak&lt;/sub&gt; (&lt;i&gt;d&lt;/i&gt; = 0.94)</td>
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<td>E</td>
<td>No significant changes from pre-training.</td>
</tr>
</tbody>
</table>

### Data

- **Lower body 1 RM (<i>d</i> = 1.16)**
- **Knee extensors peak torque (<i>d</i> = 0.33)**
- **Knee flexors peak torque (<i>d</i> = 0.50)**
- **Knee extensors RFD (<i>d</i> = 0.57)**
- **Knee extensors max RFD (<i>d</i> = 0.38)**
- **90-120-s recovery between sets**
- **Cycle ergometer**
- **20-min at 80% of HR<sub>VT</sub>**
- **25-min at 85-90% of HR<sub>VT</sub>**
- **2 sets 6 – 8 RM**
- **90 – 120-s recovery between sets**
- **VL muscle thickness (<i>d</i> = 0.07)**
- **VM muscle thickness (<i>d</i> = 0.37)**
- **VI muscle thickness (<i>d</i> = 0.40)**
- **RF muscle thickness (<i>d</i> = 0.40)**
- **QF muscle thickness (<i>d</i> = 0.60)**
- **BB muscle thickness (<i>d</i> = 0.20)**
- **BR muscle thickness (<i>d</i> = 0.32)**
- **EF muscle thickness (<i>d</i> = 0.40)**
- **VL muscle thickness (<i>d</i> = 0.35)**
- **RF muscle thickness (<i>d</i> = 0.29)**
- **Antagonist co-activation (<i>d</i> = 0.21)**
- **Neuromuscular economy VL (<i>d</i> = 0.64)**
- **Neuromuscular economy RF (<i>d</i> = 0.04)**

### Equipment

- Inclined leg press.
- Knee extension.
- Leg curl.
- Free-weight bench press.
- Lat pull-down.
- Seated row.
- Triceps curl.

### Notes

- The reverse of SE
Free-weight biceps curl.
Abdominal exercises.
Stretches and 1 x 25 reps very light loads were used as a warm-up.
Week 1
3 training days
2 sets of 18 – 20 RM

Week 2
2 training days
2 sets of 18 – 20 RM

Week 3 - 4
3 training days
2 sets of 15 – 17 RM

Weeks 5 – 7
3 training days
2 sets of 12 – 14 RM

Weeks 8 – 10
3 sets 8 – 10 RM

Weeks 11 – 12
3 training days
3 sets 6 – 8 RM

90-120-sec rest between sets

E (n = 9) – (*n = 7)
Week 1
3 training days
20-min cycle at 80% of HR

Week  2

EMG VL, RF, BF, GL.
↑ VO₂peak (d = 1.82)
↓ EMG RF 75W (d = 0.78)
↓ EMG RF 100W (d = 0.99)
2 training days
20-min cycle at 80% of
HR \(v_T\)

Week 3
3 training days
20-min cycle at 85% of
HR \(v_T\)

Week 4 – 5
3 training days
25-min cycle at 85% of
HR \(v_T\)

Week 6
3 training days
25-min cycle at 90% of
HR \(v_T\)

Week 7 - 8
3 training days
30-min cycle at 90% of
HR \(v_T\)

Week 9 - 10
3 training days
30-min cycle at 95% of
HR \(v_T\)

Week 11 – 12
3 training days
6 x 4-min/ cycle, 1-min
resting at 100% of HR
\(v_T\)

SE (n = 10) – (*n = 8)
Combined volume of S
and E training. S
preceded E. Each
A session lasted approx. 70-min.

*following with-drawls from study.

<p>|  | Ferrauti et al. 2010 | 8 women 14 men (40.0±11.7 years) | E / ES Following uncontrolled 6 month basic endurance programme an intervention was conducted over 8 weeks. E E volume = 250-min.wk Individualised for runner as their basic training + 1 x intensive 15-km at 90-95% expected marathon vel. Volume logged. ES E vol = 250-min.wk as above. S vol = 120-min.wk (2 x 60-min) Tuesday: 4 x 3-5 RM/ 3-min rest Leg press. Knee extension. Knee flexion. Hip extension. Ankle extension. Thursday: 3 x 20 – 25 RM/ 90-sec rest Reverse fly. | Tested pre- and post-intervention. E ↓ Stride length at 2.8 m.s(^{-1}) velocity ((d = 0.18)) ↓ Ground contact at 2.4 m.s(^{-1}) velocity ((d = 0.78)) Aerobic capacity: VO(_2) VO(_2) peak RPE LA concentration HR Isometric strength: Lx and Tx flexion and extension. Knee flexion and extension. Running co-ordination: Stride length. Stride frequency. ES ↑ Isometric trunk flexors ((d = 0.29)) ↑ Isometric knee extensors ((d = 1.32)) | 6/10 N/A |</p>
<table>
<thead>
<tr>
<th>Exc</th>
<th>Davis et al. 2008</th>
<th>28 females, collegiate athletes. (19.6±4 years)</th>
<th>Serial SE</th>
<th>Integrated SE</th>
<th>11 weeks training intervention (3-d-w):</th>
<th>Tested pre- and post-training intervention.</th>
<th>Serial SE</th>
<th>6/10</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td>S SE</td>
<td>Muscle strength:</td>
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<td>5-mim aerobic warm-up</td>
<td>lower body sum of mean 1RM;</td>
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<td>Repetitions to failure at 50% of 1RM x 3</td>
<td>upper body sum of mean 1RM.</td>
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<td>sets for;</td>
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<td></td>
<td>Seated inclined bilateral leg press.</td>
<td>Muscle endurance:</td>
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<td></td>
<td>Seated bilateral knee extension.</td>
<td>Comparing reps to failure at 50% 1RM.</td>
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<td>Front lat pull down.</td>
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<td>Flat bench press.</td>
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<td>Overhead shoulder press.</td>
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<td>Biceps curl.</td>
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<td>Triceps kickback.</td>
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<td>Weighted abdominal curl-up on an inclined</td>
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<td>bench.</td>
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<td>4-sec-duty-cycle.</td>
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<td>Resting for 30-60-secs between each</td>
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<td>resistance exercise.</td>
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<td>Finishing with a 30-min vigorous aerobic</td>
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<td>exercise and a cool-down</td>
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</tbody>
</table>

Muscle strength:
- Mean sum of lower body 1RM ($d = 0.89$)
- Mean sum of upper body 1RM ($d = 1.02$)

Muscle endurance:
- Mean number of leg press reps ($d = 2.20$)
- Mean number of upper body reps ($d = 0.34$)

Body composition:
- Fat free mass ($d = 0.06$)
- Mean fat mass ($d = 0.05$)
- % body fat ($d = 0.18$)

Flexibility:
- Mean reach distance ($d = 0.27$)
- Mean hand separation ($d = 0.43$)

Serial : Integrated % Change
- Lower body strength ($d = 0.80$)
- Upper body strength ($d = 0.15$)
- Leg press reps ($d = 0.3$)
I SE
20-min vigorous aerobic exercise
Repetitions to failure at 50% of 1RM x 3 sets for:
  - Seated inclined bilateral leg press.
  - Seated bilateral knee extension.
  - Seated bilateral knee flexion.
  - Front lat pull down.
  - Flat bench press.
  - Overhead shoulder press.
  - Biceps curl.
  - Triceps kickback.
  - Weighted abdominal curl-up on an inclined bench.
4-sec-duty-cycle.
Performing a 30-60-sec aerobic exercise (generally treadmill running) before each resistance exercise.

Fat free mass ($d = 0.56$)
Fat mass ($d = 0.52$)
Body fat ($d = 0.43$)
Reach distance ($d = 0.09$)
Upper body flexibility ($d = 0.59$)

<table>
<thead>
<tr>
<th>Exc</th>
<th>Mikkola et al. 2007</th>
<th>18 men 7 women Collegiate endurance athletes</th>
<th>E / SE</th>
<th>8 weeks training intervention:</th>
<th>Tested Pre- and post-training intervention.</th>
<th>SE</th>
<th>5/10</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>E SE (23.1±3.9 years)</td>
<td></td>
<td>8.8 ± 2.1h and 12.4±3.0 times/week. [19% of E hours replaced with S]</td>
<td>Strength: Isometric Concentric RFD Peak force EMG.</td>
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<td>Max aerobic running test.</td>
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</tbody>
</table>

5/10 N/A
(23.1±4.5 years) | E | 8.5±2.5 h and 9.3±1.0 times/week. | Functional tests: 30m running speed. Jump tests. Aerobic performance. Anthropometry. Resting blood samples. |
--- | --- | --- | --- |

**Exc** Mikkola et al. 2007 | 19 male endurance athletes (17.3±0.5 years) | E / SE | 8 weeks training intervention:
E (n =11) 
Training volume = 11.1 ± 3.1 h and 11 ± 1.0 times/week.
Subjects ‘usual’ endurance training (97% below aerobic threshold)

SE (n = 8) 
Training volume = 10.3 ± 1.1 h and 10 ± 0.5 times/week.
Subjects ‘usual’ endurance training (98% below aerobic threshold), but 28% was replaced with 30 – 75-min explosive strength training 3 x wk.

Sport specific double poling on roller skates | Tested pre- and post-training intervention. Muscle strength: Isometric force-time curves. Max isometric force. Bilateral concentric force production. 1 RM leg extension EMG: VL, VM of right leg. Sport specific force velocity and anaerobic measures: Max anaerobic skiing test. VO_{2, max} Anthropometry: % fat measured by skin fold thickness. | Does not specify whether SD or StE used on figures. Only % data used in text. Force curves do not include SD or StE. | 4/10 N/A |
or skis or sprinting/bounding with pole uphill. 10 – 15 x 10 – 15-s (2 – 3-m rest between sets)

Half squats, bench press, pull-over, incline row, abdominal curl, back extension, leg press, lat pull down, etc. 3 x 6 – 10 reps (3-m rest between sets)
Running sprints 3 – 6 x 30 m, alternate jumps 4 – 6 x 30 reps, skating jumps 4 – 6 x 20 reps, calf jumps 4 – 6 x 10 – 15 reps (2 – 3-m rest between sets)

<table>
<thead>
<tr>
<th>Exc</th>
<th>Jenson et al. 1997</th>
<th>8 female handball (HB) players (20.4±2.3)</th>
<th>HB training + S bias</th>
<th>1 x HB season (May – Oct)</th>
<th>Tested pre-preparation (T1) season, mid-preparation season (T2), pre-league season (T3), prior to final tournament (T4).</th>
<th>T1 - T2</th>
<th>3/10</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Prior to T1 (3 x wk) S 2 x wk 50 – 60% of 1 RM</td>
<td>Aerobic capacity: VO₂ max</td>
<td>E 1 x wk 60-min run</td>
<td>T1 – T2 (S biased) 5-7 HB training session and matches. S 2-3 x wk 1 session, 60% of 1 RM</td>
<td>Strength: Maximal isometric knee extension (was assumed) (missing data at T4)</td>
<td>Max isomet force (d = 0.05) if SD assumed (d = 0.006) if StE assumed</td>
<td>↓ Max run vel (d = 0.79) if SD assumed (d = 0.10) if SE assumed</td>
<td>↓ Max isomet force (d = 0.33) if SD assumed (d = 0.04) if SE assumed</td>
</tr>
</tbody>
</table>
2 sessions 80 – 90%
1RM ◘
E
1 -2 sprint sessions:
5 x 40.m progressive
strides
3 x 10 – 15-secs high
knee lifts
3 x 10 – 15-secs heel
flicks
5 x 100.m sprints
50 – 60-min running
(fartlek) below and up
to anaerobic threshold.

T2 – T3 (E biased)
7-10 HB training
session and matches.

S
Explosive, 75-85% of 1
RM ◘
E
60-min running below
and up to anaerobic
threshold.
3 x 8-min interval
training, 15-sec run: 15-
sec rest. (2 -4-min rest
between series)
Jump training:
6 x standing triple
jumps
4 x standing ten jumps
4 x 5 drop jumps
6 x 10 ankle jumps
10 x 12 15-min sprints
4 x 40.m progressive

T3 – T4
† VO₂max
(d = 0.11) if SD assumed
(d = 0.001) if StE assumed
† Max run vel
(d = 0.85) if SD assumed
(d = 0.11) if StE assumed
strides

T3 – T4
5 – 7 HB training
session and matches.
S
1 x wk
Explosively ◘
E
1-2 x wk
2 -3 x 7 – 10-min of 7.5
– 15-secs running: 7.5
– 15-secs rest

Jump training 1 x wk:◘

(◘ volume and or
intensity not specified in
the article)

<table>
<thead>
<tr>
<th>Exc</th>
<th>Abernethy et al. 1993</th>
<th>14 subjects.</th>
<th>Low continuous intensity E (23.2±3.3 years) / High interval intensity E (20.8±4.6 years)</th>
<th>Low E (n = 6 active ♂) 150-min cycle ergometry at 60 rpm and 35% PCE VO$_{2\text{max}}$</th>
<th>High E (n = 3 ♂ 5♀ [only 3 active gender not specified]) 5 x 5-min cycle ergometry ⇒ 5-min passive recovery at 40, 60, 80, 100 and 100% PCE VO$_{2\text{max}}$</th>
<th>Low E tested 3 x over 3 consecutive weeks 60-min prior to and following exercise intervention. High E tested 5 separate days within 7 days, 4 hours after intervention</th>
<th>Limited statistics available in text to establish d values.</th>
<th>4/10</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Low E (n = 6 active ♂) 150-min cycle ergometry at 60 rpm and 35% PCE VO$_{2\text{max}}$</td>
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<td>Limited statistics available in text to establish d values.</td>
<td>4/10</td>
<td>N/A</td>
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<tr>
<td></td>
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<td>[Low E group were significantly heavier, taller and aerobically more powerful than High E at the start of the study.]</td>
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<td>[Low E group were significantly heavier, taller and aerobically more powerful than High E at the start of the study.]</td>
<td>4/10</td>
<td>N/A</td>
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</tbody>
</table>

439
Exc  Collins et al.  1992  34 untrained subjects  SE / ES / C  7 week training intervention.  
SE (n = 10♀ 5♂) 3 x wk same day S 45-min weights, 2 x 3 – 12 reps at 50 – 90% of 1 RM, increasing weekly periodizing 2 training cycles. 
Leg press  
Leg curl  
Leg extension  
Heel raise  
Bench press  
Shoulder press  
Arm curl  
Lat pull down  
Triceps extension  
Sit ups  
E  
25-min run at 60 – 90% HRmax  
(E immediately after S)  
ES (n = 10♀ 5♂)  
(S immediately after E)  
C (n = 3♀ 1♂)  
No training  
Tested pre- and post-training intervention.  
Aerobic capacity:  
VO\text{2max}  
Strength:  
Bench press 1 RM  
Shoulder press 1 RM  
Arm curl 1 RM  
Leg press 1 RM  
SE  
↑ Bench press (d = 3.24)  
↑ Shoulder press (d = 3.84)  
↑ Arm curl (d = 6.92)  
↑ Leg press (d = 2.83)  
↑ VO\text{2max} (d = 0.10)  
ES  
↑ Bench press (d = 7.40)  
↑ Shoulder press (d = 2.98)  
↑ Bench press (d = 5.27)  
↑ Bench press (d = 4.34)  
↑ VO\text{2max} (d = 0.80)  
C  
↑ VO\text{2max} (d = 0.06)  
6/10  N/A

Exc  Hortobágyi et al. 1991  18 Army recruits & 10 college males  Low R / High R / C  3-d x 13 weeks training intervention.  
LR 2 circuits  
Stations:  
Low resistance,  
LR (n = 6/10 N/A)  
Tested pre- and post-training intervention (wk 0 – wk13)  
Anthropometry:  
Body mass  
Muscle girth  
LR  
↑ Slow knee extension (d = 0.59)  
↑ Fast knee extension (d = 0.36)  
↑ Slow knee flexion (d = 0.75)  
↑ Fast knee flexion (d = 0.50)  
↑ Free weight con forearm flexion (d = 
10) HR (n = 8)
    C (n = 10)

**Movement Vel** of \( \sim 100 \) cm.s\(^{-1}\)

- 2 Chest press/ Lat row
- 2 Upright row/ Triceps press
- 2 Bench press
- 1 Elbow flexion/ extension
- 2 Knee flexion/ extension
- 2 Jump squats
- 2 Hip adductor/ abductor

- 1 Leg thrust
- 2 Sit-ups
- 2 Row machine
- 2 Forearm & hand flexion/ extension/ pronation/ supination.
- 5-min rest

**Continuous Max Effort** 2 mile run.

**HR**
- 2 circuits

**Stations:**
- 2 higher resistance settings, movement vel of \( \sim 50 \) cm.s\(^{-1}\)
- 2 Chest press/ Lat row
- 2 Upright row/ Triceps press
- 2 Bench press
- 1 Elbow flexion/ extension
- 2 Knee flexion/ extension
- 2 Jump squats
- 2 Hip adductor/ abductor

**Strength:**
- Hydraulic resistance,
- Knee flexion/ extension
- Isokinetic bench press and squat
- Isotonic bench press and squat
- Free weights
- Isokinetic concentric/ eccentric arm flexion/ extension

**Physical Fitness:**
- 2 mile run speed
- Sit ups
- Push ups

- Free weight con forearm extension \( (d = 0.52) \)
- Free weight ecc forearm flexion \( (d = 0.36) \)
- Con 1.047 rad.s\(^{-1}\) arm extension \( (d = 0.43) \)
- Con 2.094 rad.s\(^{-1}\) arm extension \( (d = 0.55) \)

**HR**
- Slow knee extension \( (d = 1.01) \)
- Fast knee extension \( (d = 0.92) \)
- Slow knee flexion \( (d = 0.89) \)
- Fast knee flexion \( (d = 1.10) \)
- Free weight con forearm flexion \( (d = 0.54) \)
- Free weight con forearm extension \( (d = 0.42) \)
- Free weight ecc forearm flexion \( (d = 0.73) \)
- Con 1.047 rad.s\(^{-1}\) arm extension \( (d = 0.36) \)
- Con 2.094 rad.s\(^{-1}\) arm extension \( (d = 0.33) \)
<table>
<thead>
<tr>
<th>Exercise</th>
<th>Study</th>
<th>Participants</th>
<th>Intervention</th>
<th>Tested pre-, post intervention</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exc</td>
<td>Bell et al. 1988</td>
<td>16 male rowers (1 withdrew)</td>
<td>5-d per wk 40-min rowing at 75% VO$_2$max and 80 – 90% HRmax 2 x 5-weeks training intervention</td>
<td>Tested pre-, after initial 5 weeks (post 1) and after second 5 weeks (post 2).</td>
<td>Results showing improvements for peak torque and angular velocity did not give SDs or SEs, therefore d values could not be calculated.</td>
</tr>
<tr>
<td>ES</td>
<td></td>
<td>ES (n = 8)</td>
<td>Increasing 5-min per week until 60-min achieved</td>
<td><strong>ES</strong>&lt;br&gt;[Pre – Post 1]↑ Absolute VO$_2$max $(d = 0.21)$&lt;br&gt;[Pre – Post 2]↑ Absolute VO$_2$max $(d = 0.17)$</td>
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<tr>
<td>SE</td>
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<td>ES (24±1.3 years)</td>
<td></td>
<td><strong>SE</strong>&lt;br&gt;[Pre – Post 1]↑ Absolute VO$_2$max $(d = 0.28)$&lt;br&gt;[Pre – Post 2]↑ Absolute VO$_2$max $(d = 0.59)$</td>
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<tr>
<td>C</td>
<td></td>
<td>ES (22±1.0 years)</td>
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<td><strong>C</strong>&lt;br&gt;[Pre – Post 1]↓ Absolute VO$_2$max $(d = 0.05)$</td>
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<td>ES (23±1.4 years)</td>
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</tbody>
</table>

1 Leg thrust
2 Sit-ups
2 Row machine
2 Forearm & hand flexion/ extension/ pronation/ supination
5-min rest
Continuous max effort 2 mile run.

C
No training
flexion/extension
Unilateral seated elbow flexion/extension
Bilateral supine elbow flexion/extension
Horizontal shoulder abduction/adduction
Bilateral standing elbow flexion/extension
Shoulder abduction/adduction
Bilateral reclined hip and knee extension
Bilateral recline elbow flexion/extension
Supine unilateral shoulder abduction/adduction
Progression from 2 to 3 circuits by end of week 2, with a 4-min rest between circuits.

SE (n = 7)
As above, but S preceded E

C (n = 8)
Tested over 5 week period prior to training intervention.
Table Abbreviation  Key:

<table>
<thead>
<tr>
<th>ANC</th>
<th>Anaerobic Capacity</th>
<th>BB</th>
<th>Biceps Brachii</th>
<th>BF</th>
<th>Biceps Femoris</th>
<th>BMI</th>
<th>BR</th>
<th>Brachioradialis</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT</td>
<td>Basic Training</td>
<td>BTE</td>
<td>Basic Training and cardio-vascular Endurance</td>
<td>BTS</td>
<td>Basic Training and Strength</td>
<td>C</td>
<td>Control</td>
<td>con</td>
</tr>
<tr>
<td>CSA</td>
<td>Cross-sectional Surface Area</td>
<td>C-SE</td>
<td>Concurrent Strength and (cardio-vascular) Endurance</td>
<td>CT</td>
<td>Computerised Tomography</td>
<td>d-w</td>
<td>days per week</td>
<td>E</td>
</tr>
<tr>
<td>ecc</td>
<td>eccentric</td>
<td>EMG</td>
<td>Electromyogram</td>
<td>ES</td>
<td>Endurance (cardio-vascular) and Strength</td>
<td>EVO₂ max</td>
<td>Estimated VO₂MAX</td>
<td>Exl</td>
</tr>
<tr>
<td>LA</td>
<td>Lactic Acid</td>
<td>Lx</td>
<td>Lumbar</td>
<td>h</td>
<td>Hour(s)</td>
<td>HB</td>
<td>Handball</td>
<td>HR</td>
</tr>
<tr>
<td>HRR</td>
<td>Heart Rate Recovery</td>
<td>HRVT</td>
<td>Heart Rate Variability Threshold</td>
<td>Max</td>
<td>Maximum</td>
<td>.m</td>
<td>minute(s)</td>
<td>MRI</td>
</tr>
<tr>
<td>N-SE</td>
<td>Non-concurrent Strength and Endurance (cardio-vascular)</td>
<td>PANP</td>
<td>Peak anaerobic power</td>
<td>QF</td>
<td>Quadriceps Femoris</td>
<td>RPE</td>
<td>Rate of Perceived Exertion</td>
<td>reps</td>
</tr>
<tr>
<td>RF</td>
<td>Rectus Femoris</td>
<td>RFD</td>
<td>Rate of Force Development</td>
<td>RM</td>
<td>Repetition Maximum</td>
<td>S</td>
<td>Strength</td>
<td>SD</td>
</tr>
<tr>
<td>SE</td>
<td>Strength and Endurance (cardio-vascular)</td>
<td>STE</td>
<td>Standard Error</td>
<td>-sec</td>
<td>Second(s)</td>
<td>Tx</td>
<td>Thoracic</td>
<td>TB</td>
</tr>
<tr>
<td>US</td>
<td>Ultra-Sound</td>
<td>VI</td>
<td>Vastus Intermedius</td>
<td>VL</td>
<td>Vastus Lateralis</td>
<td>VM</td>
<td>Vastus Medialis</td>
<td>VO₂ max</td>
</tr>
<tr>
<td>VO₂ peak</td>
<td>Peak Oxygen uptake</td>
<td>VT₂</td>
<td>Second Ventilatory Threshold</td>
<td>↑</td>
<td>Increase</td>
<td>↓</td>
<td>Decrease</td>
<td>↑</td>
</tr>
<tr>
<td>♂</td>
<td>Male</td>
<td>♀</td>
<td>Female</td>
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Appendix E:

Patient Participation Information Sheet
PARTICIPANT INFORMATION SHEET

The effects of non-concurrent strength and endurance rehabilitation following in anterior cruciate ligament reconstruction and autologous chondrocyte implantation surgery to knees. Randomised controlled trials.

You are invited to take part in the research study named above. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Talk to others about the study if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether you wish to take part.

What is the purpose of the study?

This is an educational study to see if we can improve upon the rehabilitation you receive following your surgery involving either:

(a) anterior cruciate ligament (ACL) reconstruction surgery, detailed in the ACL patient advice booklet.

Or

(b) autologous chondrocyte implantation (ACI) surgery, detailed in the ACI patient advice booklet.

Examples of the type of exercises you will be required to do following surgery are highlighted in these booklets. The exercises will be a combination of both strength and endurance.

Strengthening exercises include lifting, pushing or pressing heavy weights a short number of times, usually three sets of five repetitions.

Endurance exercises use lighter weights, but more repetitions, usually about three sets of twenty repetitions. Endurance exercise will also involve the heart and lungs working more, for example cycling, rowing, jogging, and swimming for longer than twenty minutes at a time.

After the surgery, the types of exercises you perform will be limited at certain times during your recovery. This is due to the stages of healing. The study will not alter this.

The study will look to see if there is any difference when you perform strength and endurance exercises on separate occasions rather than together in the same session. When you perform strength and endurance exercises separately, it is called non-concurrent training/rehabilitation and when you perform strength and endurance exercises in the same session, it is called concurrent training/rehabilitation.
Why have I been chosen?

In this study, we will investigate patients who have elected to undergo either ACL reconstruction or ACI knee surgery and who are otherwise medically fit to participate in rehabilitation following this surgery at RJAH. The reason we asked you to take part in this study is that you fit this description.

Do I have to take part?

No. You can refuse to take part in this research. You do not have to give a reason. You can also change your mind and withdraw from the research at any time. Please tell us should you wish to do so. If you wish to withdraw from the research, your relationship with the physiotherapist, the consultant, and anyone else involved in your care and the standard of treatment that you receive will not be affected in any way.

What will happen to me if I take part and what would I have to do?

We would like to find out whether or not the current way of rehabilitating patients who have had your type of surgery (either ACL or ACI) could be improved upon. To find out, we need to make comparisons between the different ways of rehabilitating. To do this, we put people into groups and give each group a different style of rehabilitation; the results are compared to see which one, if any is better. To try to make sure the groups are the same to start with, each participant is put into one of three groups by chance (randomly).

All groups will follow the same basic rehabilitation protocol for either ACL or ACI depending on the surgery you have undergone. However, the rehabilitation will be packaged slightly differently and the number of assessments you have for the purpose of the study will vary.

All groups will be assessed before surgery and at 48 weeks after surgery. These are the assessments that will give us the majority of the information required for the study.

In addition, some groups will be tested at intermediate stages during this period.

In order to get the best results it is better that you are unaware of the precise differences between each group. Although you will not be told which group you belong to, your physiotherapist will discuss with you exactly what exercises to do each time you visit for physiotherapy.

The assessments are expected to take up to one hour and they will take place on a day that you would normally attend either outpatient clinic or physiotherapy. All groups will be asked to keep a weekly rehabilitation diary and it is anticipated the diary entry should take no longer than 10 minutes per week over the 48-week period. The total study time commitment including assessments and diary entries required for each group will be a minimum of 10 hours to a maximum of 14 hours.
The assessments you are agreeing to allow us to assess your progress. We will be monitoring aspects of knee joint performance such as:

(1) The strength of your leg muscles and your ability to repeat brief strength tasks accurately. This allows us to check how well the muscles can produce force to protect the joint efficiently.

(2) How quickly your leg muscles can react to a brief and painless magnetic pulse. This allows us to safely check how quickly the muscles could produce force to protect the joint in an emergency, such as if you were to trip or land awkwardly from a jump.

(3) The laxity/looseness of your knee will also be tested. This allows us to check how well the rehabilitation is affecting stability of the joint.

(4) How the above factors change following a brief fatigue task. This allows us to check the extent to which muscle fatigue could lessen your ability to protect the joint during exercise and helps us to gauge a safe return to sport or work-related activities.

(5) You will also be asked to complete questionnaires about your knee and keep a weekly diary of your rehabilitation. This will help us understand how you feel and compare it to the more physical outcomes. It will also tell us how much physical activity you are doing.

What will happen if I do not take part?

Depending on whether you have ACL or ACI surgery you will undergo the standard concurrent rehabilitation designed for that particular procedure and will not have the extra assessments or have to keep a weekly rehabilitation diary. Your treatment and relationship with the professionals responsible for your care will not be affected in anyway.

What are the possible disadvantages and risks and what are the possible benefits of taking part?

No matter what group you are in, there will be no extra clinical risks or disadvantages. This is because you will all be performing the same exercises at the same stage during your recovery. It is only the sequencing of the exercises that is being monitored to see if this affects the outcome of the rehabilitation.

It may be that one group makes a speedier recovery.

We cannot promise being involved in this study will help you more than the routine rehabilitation, but the information we get might help improve the treatment of future patients following ACL or ACI surgery.
What happens when the research study stops?

The research may tell us if one way of rehabilitating is better than another. This will then alter the way we suggest patients rehabilitate in the future.

If you wish, after the research is complete we will give you the results.

The results may also be written and published in medical/scientific journals to help other clinicians and patients elsewhere. You will not be identified in these results.

Expenses and payments:

As this study will not involve any ‘extra’ visits to the hospital, you will not be allocated any expenses or payments.

What if there is a problem?

In the highly unlikely event you are harmed in any way by taking part in this study, there are no special compensation arrangements, unless you are harmed by someone’s negligence. Then you may have grounds for a legal action but you may have to pay for it. Regardless of this, if you wish to complain, or have any concerns about any aspect of the way you have been approached or treated during the course of this study, you should ask to speak with one of the researchers who will do their best to answer your questions (see contact details). If you remain unhappy and wish to complain formally, you can do this through the NHS Complaints Procedure (or Private Institution). Details can be obtained from the hospital.

Will my taking part in the study be kept confidential?

The only purpose of this educational study is to assess the best way to rehabilitate after ACL or ACI surgery. We will keep your name, age, sex and results of the measurements in a record that will be stored on a password-protected computer to ensure only persons involved in the study can access them. The storage and subsequent destruction of your data are compliant with the Data Protection Act 1998. All information that is collected about you during the course of the research will be kept strictly confidential. Any information about you that leaves this hospital will have your name and address removed so that you cannot be recognised from it.
Contact Details:

For further information about this study or any queries regarding your rehabilitation, please contact,
Mon – Fri, 9am – 5pm:

Andrea Bailey MCSP SRP
Supt Sports Injury Physiotherapist
Physiotherapy Dept
RJAH Orthop & Dist NHS Trust
Gobowen
Oswestry
Shropshire
SY10 7AG
Tel 01691 404160
E-mail: andrea.bailey@rjah.nhs.uk

ACL and ACI Patient Advice Booklets

You will be given the appropriate booklet before your surgery regardless of whether you take part in this study or not. This booklet will give you some insight and understanding about your surgery and rehabilitation. If you have not received this booklet please make contact using the details above and one will be sent to you. Alternatively, you can download the booklets from www.sports-surgery.co.uk

Who has reviewed the study?

This study was given a favourable ethical opinion for conduct in the NHS by the Shropshire Local Research Ethics Committee and approved for scientific merit by the Research Panel at RJAH.

If you agree to take part, you will be given this Information Sheet and a signed consent form to keep.

Thank you for considering taking part and/ or taking time to read this sheet.
Appendix F:

Thesis Participation Consent Form
PATIENT CONSENT FORM

Hospital number: 
Study Number: 
Patient Identification Number for this trial:

CONSENT FORM

Name of Researcher: ________________________________

(1) I confirm that I have read and understand the information sheet dated ____________ for the above study and have had the opportunity to ask questions.

(2) I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason, without my medical care or legal rights being affected.

(3) I understand that sections of any of my medical notes may be looked at by responsible individuals from The National Centre for Sports Injury Surgery or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to my records.

(4) I agree to take part in the above study.

Name of Patient  Date  Signature
______________________________  __________________  _____________

Name of person taking consent (if different from researcher)  Date  Signature
______________________________  __________________  _____________

Researcher  Date  Signature
______________________________  __________________  _____________

Parental consent is required for participants under 18 years of age.
I am the parent/ legal guardian of the above mentioned individual.

Name __________________________  Address __________________________
________________________________  __________________________________
________________________________  __________________________________

Signed __________________________

Date __________________________
Appendix G:

Performance Profile Score Chart
PERFORMANCE PROFILE EXAMPLE

How does your injured limb feel at the present time compared with your non-injured limb, on each of the qualities you have listed?

Response scale
(1) ‘extremely different to my non-injured limb’
(10) ‘the same as my non-injured limb’
Appendix H:

Revised RJAH anterior cruciate Ligament

Rehabilitation Guide
**RJAH ACL Reconstruction Guide**

**Note to Therapist:**  
*This is a guide to progression, not an exhaustive list of rehabilitation and does not replace clinical reasoning.  
*Treat any soft tissue symptoms on their merit.  
*Objective Tests can be used as an indication for progression.  
*Special Instruction(s) includes specific post-operative advice for the individual patient based on their surgeon’s recommendation (as applicable). This will be completed on discharge or follow-up clinic appointments.

<table>
<thead>
<tr>
<th>PHASE OF REHABILITATION</th>
<th>IDEAL CRITERIA</th>
<th>REHABILITATION GUIDE</th>
<th>GOALS</th>
<th>OBJECTIVE TEST</th>
<th>SPECIAL INSTRUCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHASE 1</td>
<td></td>
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</tbody>
</table>
| From Day 1               | o Successful operative outcome | • Cryocuff/Ice  
  • Patella mobilisations [if PTG]  
  • EOR E mobilisations  
  • H and calf stretches [care if H graft]  
  • Ankle Exercises (e.g. heel raises)  
  • SQ progressing to SLR  
  • Co-contraction Q and H  
  • Prone SLR  
  • Mini squats/ small knee bends  
  • Weight transferring  
  • Elbow crutches for comfort | 1. Reduce inflammation  
  2. Gain terminal E  
  3. Promote distal circulation  
  4. Gradually regain ROM  
  5. Increase confidence  
  6. Promote early mobility |                |                     |
<table>
<thead>
<tr>
<th>PHASE OF REHABILITATION</th>
<th>IDEAL CRITERIA</th>
<th>REHABILITATION GUIDE</th>
<th>GOALS</th>
<th>OBJECTIVE TEST</th>
<th>SPECIAL INSTRUCTION</th>
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<tr>
<td>PHASE 2</td>
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<tr>
<td>From Week 1</td>
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<tr>
<td></td>
<td>o Full active and passive movement</td>
<td>- Static Bike or Turbotrainer no/low resistance as tolerated (part revolution → full revolution as symptoms dictate)</td>
<td>1. Promote early function</td>
<td>AROM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Mobilise independently +/- aids</td>
<td>- Gradually increase weight-bearing</td>
<td>2. Increase ROM</td>
<td>PROM</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td>- Independent gait re-education</td>
<td>3. Encourage FWB</td>
<td></td>
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<td></td>
<td></td>
<td>- Low step-touch → step-up → step over</td>
<td>4. Improve muscular control</td>
<td>SLR</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>[avoid ‘heavy’ eccentric Q if PTG]</td>
<td></td>
<td></td>
<td>Effusion</td>
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<tr>
<td></td>
<td></td>
<td>- Active OKC Q 90º - 45º</td>
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<td></td>
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<td>- Other muscle groups not to be neglected</td>
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<td></td>
<td></td>
<td>- Upper body active exercise → resis/reps/sets/speed</td>
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<tr>
<td>PHASE OF REHABILITATION</td>
<td>IDEAL CRITERIA</td>
<td>REHABILITATION GUIDE</td>
<td>GOALS</td>
<td>OBJECTIVE TEST</td>
<td>SPECIAL INSTRUCTION</td>
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<td>PHASE 3</td>
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<td>From Week 2</td>
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<tr>
<td></td>
<td>○ Minimal discomfort</td>
<td>● Gait with predictable changes in direction</td>
<td>1. Progress functional activities</td>
<td>Single Leg Stance</td>
<td></td>
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<tr>
<td></td>
<td>○ FWB</td>
<td>● Prone auto-over press F → develop into Q stretch</td>
<td>2. Prevent AKP</td>
<td>Clam</td>
<td></td>
</tr>
<tr>
<td></td>
<td>○ SLR with no lag</td>
<td>● Step-ups (for/back/sideways/over) → height/reps/speed</td>
<td>3. Prevent scar adherence</td>
<td>Planks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>○ AROM = Full E - ≥100°</td>
<td>● PWB (parallel bars) jumps, hops, leaps → control technique/speed/reps</td>
<td>4. Prevent joint stiffness</td>
<td></td>
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<td></td>
<td></td>
<td>● Leg Press/Squats → resis/reps/sets/speed</td>
<td>5. Restore normal gait pattern</td>
<td></td>
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<td></td>
<td></td>
<td>● Proprioception → single leg stance/wobble boards/Trampette/crash mats/etc.</td>
<td>6. Promote appropriate muscle strength, power and endurance</td>
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<td></td>
<td></td>
<td>● Gymball and Theraband work</td>
<td>7. Improve neuromuscular/proprioception/sensorimotor performance</td>
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<td></td>
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<td>● Lower body active exercise [exception of OKC Q. Respect Q or H graft site as applicable] → resis/reps/sets/speed</td>
<td>8. Maintain cardio-vascular fitness</td>
<td></td>
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<td></td>
<td></td>
<td>● Muscle balance exercises as appropriate</td>
<td>9. Encourage patient compliance</td>
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<td></td>
<td>● Core stability exercises as appropriate</td>
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<td>● Flexibility exercises as appropriate</td>
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<td>● Rowing → dist./speed/resis</td>
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<td>● X-Trainer → dist./speed/resis</td>
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<td>● Hydrotherapy (AVOID breaststroke leg kick until Month 3)</td>
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<td>PHASE OF REHABILITATION</td>
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<td>PHASE 3</td>
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<td></td>
<td>Single Leg Squat 60º</td>
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<td>From Week 6</td>
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<tr>
<td></td>
<td>o Normal symmetrical gait</td>
<td>• Train strength and endurance 3 – 4 x per week</td>
<td>1. Promote appropriate strength, power and endurance based on individuals needs</td>
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<tr>
<td></td>
<td>o Full AROM</td>
<td>• Train strength and endurance on separate days</td>
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<tr>
<td></td>
<td>o No/minimal effusion</td>
<td>• Have a minimum of 24 hours between strength days</td>
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<tr>
<td></td>
<td>o Single leg stance ≥80% parity</td>
<td>• Strength: 10 – 20 min CV warm-up (exception of jogging/running)</td>
<td>2. Improve neuromuscular performance</td>
<td></td>
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<tr>
<td></td>
<td>o Clams 10 reps with 10 sec hold ideal control [L] &amp; [R]</td>
<td>Choose a load 1 – 12 RM</td>
<td>3. Increase confidence</td>
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<tr>
<td></td>
<td>o Directional Planks 30 sec hold ideal control</td>
<td>Choose numbers of sets and rest time between sets</td>
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<td></td>
<td></td>
<td>Alternate upper/lower body exercises within session</td>
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<td>Moderate to fast speed under control</td>
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<td></td>
<td></td>
<td>Vary load/set/rest between sessions</td>
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<td>[include OKC Q from week 10]</td>
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<td>Adjust if necessary based on symptoms</td>
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<td>• Endurance: Gradually progress toward ≥45 min continuous CV exercise (exception of jogging/running)</td>
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<td>Choose a load 15 – 20 RM</td>
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<td></td>
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<td>Choose numbers of sets and rest time between sets</td>
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<td>Alternate upper/lower body exercises within session</td>
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<td>Moderate to fast speed under control</td>
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<td>Vary load/set/rest between sessions</td>
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<td></td>
<td></td>
<td>[include OKC Q from Week 10]</td>
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<td></td>
<td>Adjust if necessary based on symptoms</td>
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<td></td>
<td></td>
<td>• Add FWB double footed plyometrics from Week 10</td>
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<tr>
<td></td>
<td></td>
<td>control technique/speed/reps</td>
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<table>
<thead>
<tr>
<th>PHASE OF REHABILITATION</th>
<th>IDEAL CRITERIA</th>
<th>REHABILITATION GUIDE</th>
<th>GOALS</th>
<th>OBJECTIVE TEST</th>
<th>SPECIAL INSTRUCTION</th>
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</thead>
<tbody>
<tr>
<td>PHASE 4</td>
<td></td>
<td><strong>PHASE 4</strong></td>
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</tbody>
</table>
| From Week 12             | Single Leg Squat 60° 5 sec hold with good alignment | o Progress to single footed plyometrics as dictated by control  
o Introduce jogging → running when Q strength and control is adequate  
o Advance dynamic proprioceptive exercises e.g. volleying football, throwing, catching, racket and ball while balancing on trampoline | 1. Sport specific function | Tuck Jump |                   |
| Phase 5                  |                | **Phase 5**           |       |                |                   |
| From Week 16             | As a PHASE 4 | o As a PHASE 4  
|                          |                | o Add agility drills [From Week 16] when sufficient control and confidence is achieved e.g. twist/turn/pivot/cut/accelerate/ decelerate/ direction  
|                          |                | Progress from predictable agility to unpredictable  
|                          |                | Perturbation training e.g. therapist randomly nudges patient off balance during a single leg throw-catch drill | 1. As PHASE 4 | As PHASE 4 |                   |
| PHASE 6                  |                | **PHASE 6**           |       |                |                   |
| From Week 20             | Tuck Jump ≥ 60% quality  
5 RM > 80% parity  
Hop for distance >80% parity | o Tuck Jump ≥ 60% quality  
5 RM > 80% parity  
Hop for distance >80% parity  
|                          |                | o Non-contact sport specific training → terrain/volume/periodisation | 1. Prepare neuromuscular and psychological ability to return to unrestricted function | As indicated for individuals goals |                   |
PHASE 7
From Week 24

- All Tests > 90% parity
- Contact sport specific training
- Earliest return to contact sport training
- Progress to full restriction free sports and activities [dependent on Consultant opinion]

1. Unrestricted confident function
2. Injury prevention

Terminology Key:

<table>
<thead>
<tr>
<th>Key</th>
<th>Definition</th>
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<tbody>
<tr>
<td>PTG</td>
<td>Patella Tendon Graft</td>
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<tr>
<td>EOR</td>
<td>End of Range</td>
</tr>
<tr>
<td>E</td>
<td>Extension</td>
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<td>F</td>
<td>Flexion</td>
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<tr>
<td>SLR</td>
<td>Straight Leg Raise</td>
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<tr>
<td>Q</td>
<td>Quadriceps</td>
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<td>H</td>
<td>Hamstrings</td>
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<tr>
<td>AKP</td>
<td>Anterior Knee Pain</td>
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<td>R</td>
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<td>Partial Weight Bear</td>
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<td>Full Weight Bear</td>
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<td>Open Kinetic Chain</td>
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